

Research Article

The Experimental Study on Concrete Permeability of Wireless Communication Module Embedded in Reinforced Concrete Structures

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Recently, as the information industry and mobile communication technology develop, their study is conducted on the new concept of intelligent structures and maintenance techniques that apply wireless sensor network, USN (Ubiquitous Sensor Network), to social infrastructures such as civil and architectural structures on the basis of the concept of Ubiquitous Computing, which invisibly provides human life with computing, along with mutually cooperating, compromising, and connecting networks to each other by having computers within all objects around us. The purpose of this study is to investigate the capability of wireless communication of sensor node embedded in reinforced concrete structure with a basic experiment on electric wave permeability of sensor node by fabricating molding with variables of concrete thickness and steel bars that are mostly used in constructing structures to determine the feasibility of application to constructing structures with USN. By installing wireless communication module inside the structures, it is possible to communicate to measure the pitch of steel bars and permeability of concrete, by measuring in both directions horizontally and vertically. The magnitude of an electric wave in the range of used frequencies was measured by using Spectrum Analyzer. This electric wave was numerically analyzed and the effective wavelength of frequencies was analyzed by the properties of a frequency band area. As a result of constructing structures with wireless sensors, Plain concrete showed 45 cm for depth of permeability. Reinforced concretes that has pitches of 5 cm showed 37 cm and pitches of 15 cm showed 45 cm for the depth of permeability. This suggests that if the pitch of steel bars was more than 15 cm, it would not affect wireless communication.

1. Introduction

Structural health monitoring and damage detection have been of great concern in the design, operation maintenance, and repair of many civil structures. In order to monitor the health of large infrastructures such as bridges, highways, buildings, and dams, the outputs from various kinds of sensors were installed at different places in civil structures data collected simultaneously and/or sequentially [1].

Besides, as the recent information industry and mobile communication technology are developed by using the wireless sensor network technique. USN (Ubiquitous Sensor Network), with the concept of Ubiquitous Computing, which invisibly provides information to human with computing along with mutually cooperating, compromising, and connecting networks to each other by having subminiature

computers within all objects around us, is being tried mainly by the information and communication industry [2, 3].

The measuring of sag as cracks in bridge structures is measured by the wireless measurement sensor in the field of bridges, and the ubiquitous bridge system that is monitoring erosion by the water flow on the lower part of pier is partly applied but the environment based on complete ubiquity is not established [4, 5]. In addition, there is the displacement measurement device that measures the sinking amount of tunnel works and displacement inside tunnels before and after an explosion using wireless optical fiber in tunnels, and the system for searching and maintaining underground structures by attaching RFID tags to underground structures having USN and the field application like the automatic sluice control system that monitors and controls the level of water is being attempted [6, 7].

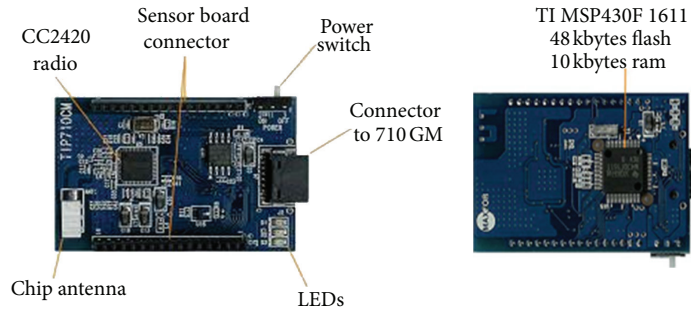


FIGURE 1: Structure detailed of cc2420.

The depth of permeability of concrete by frequencies and the effect of the pitch of steel bars with Active RF wireless communication module embedded into concrete for structuring ubiquitous structures as a basic experiment for an application to construction industry were looked into in this study.

For this, specimens were made of concrete and bars that are mostly used for construction of structures while wireless communication modules were installed inside them, the possible communication distance and the intensity of electric waves were measured. The effect of the length of wavelength of frequencies was analyzed according to the properties of the frequency band. This is to suggest the basic data for constructing social infrastructure having the concept of ubiquity for the real-time monitoring of the level of displacement and damage inside the structure as well as external damage by embedding a wireless sensor in social infrastructure through this.

2. Background

In this study, we measured the transmittance and radio signal strength of a sensor which was embedded in the structure using USN. The fundamental experiments were conducted to prevent symptom like demolition, crack, corrosion, and fire through the determination whether or not the embedded sensor works in construction structure [8].

Recently studies that find corrosion and cracks and defects in the concrete structure using radio waves transmission characteristics, such as "Radiowave Propagation through Window Panes and Reinforced Concrete Structure" research [9], are in progress. There is no enough study about the radio wave attenuation but we did experimental work about the radio wave attenuation effects depending on depth, thickness, and amount of reinforcing steel using the test piece.

3. Devices for Experiments

How much steel bars and concrete, which are the main materials of the construction of structures, affect transmitting and receiving of electric waves was analyzed as a basic experiment for the field application of a wireless sensor network for civil and architectural structures. The possible communication distance by the thickness of wireless communications modules installed inside plain concrete and reinforced concrete

and the communication distance by the pitch of steel bars were measured, the waveform of electric waves by thickness was measured, the phenomenon of diminution of electric waves was evaluated by using a Spectrum Analyzer, and the effect of the length of frequency wavelength according to the properties of the frequency band was analyzed [10].

3.1. Materials for Experiments. Various sized specimens (e.g, $600 \times 600 \times 100$ (mm)) were made with variables of the concrete thickness, the pitch of steel bars, the direction of electric waves, and the intensity of RF power. When making specimens, OPC (Ordinary Portland Cement) that meets KS F 5201 and has specific gravity of 3.15 and fineness of 3,341 and the maximum size of aggregate having 13 mm Φ , specific gravity of 2.65, and fineness modulus of 2.9 were used. Small aggregates that have specific gravity of 2.62 and standard sand were used. Meanwhile, deformed bars with the 16 mm diameter were placed.

3.2. Equipment for Experiments

3.2.1. Module. By installing sensor module RF chip having frequency of 2.4 GHz inside the model and starting to receive wireless signals from the sensor while transmitting any change in temperature, humidity, and illuminance, the detailed structure of the sensor is as shown in Figure 1.

3.2.2. Spectrum Analyzer. Spectrum Analyzer used is the equipment indicating the result of measurement by the spectrum of signal or frequency band on a screen and shows what intensity range signals of certain frequency elements have [11]. The unit of horizontal axis is shown as kHz/Div and MHz/Div, which are called Span/Div (frequency span of horizontal axis). Spectrum Analyzer of model R3131A (Figure 2) was used in this experiment with frequency of 2.4 GHz and Span/Div of 50 MHz, and the result value was represented with dBm (the intensity of electric waves).

3.2.3. Chip Antenna. The pattern of radiation of Chip antenna that was attached to used module is the way of OMNI-DIRECTIONAL (Figure 3). The real size of Chip antenna is $8.0 \times 4.0 \times 1.5$ mm, which is small and light, and it provides several data channels to a single transmission medium using FDMA (Frequency Division Multiple Access) as broadband and the output ratio against input such as



FIGURE 2: Spectrum Analyzer.

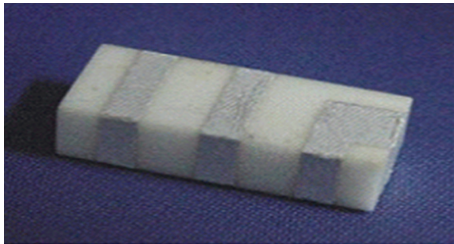


FIGURE 3: Chip antenna.

receiving an amplifier is high up to 1.5 dBi and it shows linear polarization [12, 13].

4. Methods of Experiments

4.1. Fabrication of Specimen. To experiment the capability of wireless communication in plain and reinforced concrete, the base plate that was grooved to put a module and plain concrete specimens with various thickness (Figures 4 and 5) were made and concrete was placed with steel bars in the pitches of 5, 7, 10, and 15 cm, respectively [14]. The mixture of concrete followed KS standard mixture, and when placing concrete, the dimension of a specimen was 600×600 (mm) in length and width in case of vertical penetration experiment and five of each 1, 3, 5, and 20 (cm) by the thickness were made, respectively. Besides, the length and width are 600×100 (mm) in horizontal direction and five specimens of each 1, 3, 5, and 20 (cm) by the thickness were made, respectively [15, 16].

4.2. Methods of Measurement of Receiving Distance. Aluminum foil and special case were used to block off effects of electric waves from the bottom and the side in case of an experiment of vertical-oriented electric waves permeability and from the bottom and upwards in case of an experiment of horizontal-oriented electric waves permeability. Besides, the transmission of data was confirmed by using monitoring system (Figure 6). After node number is designated for each module that was transmitted, the number of node is designated as 0 that can receive a reception. Once communication started, the state of receiving by each node could be checked by linearly connecting nodes (Figure 6) and in case that communication is cut, which could be known by the change

of color of node number. Moreover, if each node number was chosen, the value of sensors for temperature, humidity, and illuminance that were installed in each selected node could be identified. The state of transmission of module installed inside concrete was checked through linear connection (Figure 6) on the basis of the baseplate with the change of concrete thickness. The exact intensity and loss of electric waves cannot be known since only the possibility of transmission can be checked and the intensity of transmission of electric waves is not measured in this program. For this, intensity and the loss of electric waves were analyzed by concrete thickness using Spectrum Analyzer.

4.3. Test of Distance of Transmission and Reception in Free Space. First, the capability of module was experimented and the capability of transmission in free space (Figure 7) was experimented for the comparison of the value of the experiment result. The experiment was executed in a play yard of H University in Seoul at 2 p.m. when there would be the least humidity in the air to minimize the effect of external environment.

After fixing transmission module on the starting point, the distance of transmission was measured by gradually making the distance be farther.

4.3.1. The Result of Test of Distance of Transmission and Reception in Free Space. As a result, it was possible to transmit and receive up to the end of the play yard with the length of 200 m in free space. Since it is not possible to experiment further, this experiment assumed that it was possible to receive from the distance more than 200 m in free space. The result shows that it is possible to use sensors with exposure to the outside without embedding them into the structure.

As a result of the experiment on communication distance (Figure 8), the quality of communication was 86% in case of 120 m and 56% in case of 300 m, which means it is more than 50% from both 120 m and 300 m (Figure 9), and it was determined to be satisfactory to apply to civil and architectural structures [17].

4.4. Permeability Experiment in Vertical Direction. For the experiment of permeability in vertical direction, after putting the baseplate on the far bottom in the specially fabricated case (Figure 10), R31 and R15 that have the intensity of RF with 31 dB and 15 dB, respectively, were embedded.

For more accurate experiment, transmission module S31 that was specially fabricated to enable only each other communication was embedded more than once and the experiment was conducted. Unlike R31, R15 was transmitted through a computer. If transmission module sent a signal, the lamp itself of reception module would be lit and indicate that transmission and reception are in progress. In addition, the experiment was executed by setting equally RF intensity of both R31 and S31 as 31 dB and the comparison between R31 received through a computer program and S31. The module of transmission and reception, that was specially fabricated, made it possible to experiment with more accuracy.

The possible distance of reception with piling up concrete plates (Figure 11) was measured in this experiment.



FIGURE 4: Placement of bars (D16@10, D16@5).



FIGURE 5: Concrete placement.

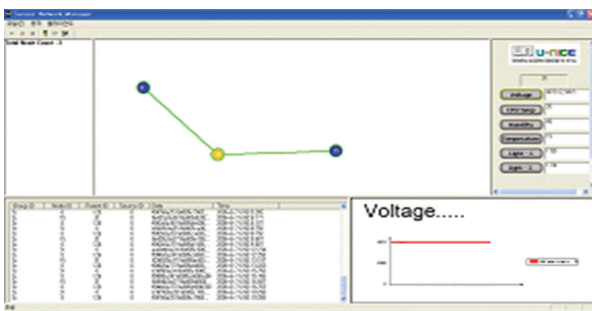


FIGURE 6: Monitoring system.



FIGURE 7: Free space transmission and receiving test.

4.5. Permeability Experiment in Horizontal Direction. In the same way with permeability experiment in vertical direction for the method of this experiment, the depth of permeability in horizontal direction was measured (Figure 12). The distance of transmission and reception was measured with the baseplate on the right side and piling up in horizontal direction on the left using variously fabricated concrete with thickness of 1, 3, 5, and 20 cm. The experiment was implemented by using the module of transmission and reception R15, R31, and S31 that were used in the experiment of permeability in vertical direction.

4.6. Test of Attenuation of Electric Waves. In the experiment of permeability in vertical and horizontal directions that was



FIGURE 8: Measurement scene and results in the 120 m.

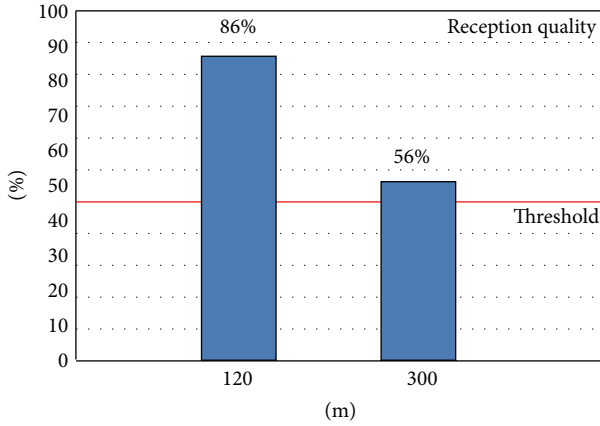


FIGURE 9: Communication results in 120 m and 300 m.

conducted above, since it was possible only to check the feasibility of transmission of wireless communication and the intensity of transmission of electric waves could not be checked, it was impossible to know the accurate intensity and loss of electric waves by the thickness of concrete. For this, the intensity and loss of electric waves by concrete thickness were measured and analyzed using Spectrum Analyzer (Figure 13). The object of this experiment was R31 that had the biggest intensity of RF. With the same way as the above, experiment spectrum in free space was measured to compare the value of the experiment. Furthermore, it was measured by every 10 cm in case of plain concrete and by changing the pitch of steel bars in reinforced concrete.

5. The Result and Analysis of the Experiment

5.1. Permeability Experiment in Vertical Direction. The result of permeability in vertical direction is shown in Table 1. In case of R15, it showed 39 cm for the depth of permeability in plain concrete and 31 cm for D16@5 which means that the pitch of steel bars is 5 cm, 34 cm for D16@7 which means that the pitch of steel bars is 7 cm, 36 cm for D16@10 which means that the pitch of steel bars is 10 cm, 38 cm for D16@15 which means that the pitch of steel bars is 15 cm in reinforced concrete. In case of R31, it penetrated up to 45 cm in plain concrete, 37 cm for D16@5, 40 cm for D16@7, 42 cm for D16@10, and 45 cm for D16@15. S31 showed the same results. As a result, when R15 and R31 were compared, it was suggested that the bigger the intensity of RF is, the more it penetrates.

Moreover, on comparing all of R15, R31, and S31 it penetrated better when the pitch of steel bars was 15 cm rather than 5 cm and it did the best in plain concrete. And Figure 13 shows that the depth of penetration increases linearly as the pitch of steel bars get bigger, which means wireless communication is affected by the pitch of steel bars. In addition, Figure 14 shows that when the pitch of steel bars is more than 15 cm the pattern of permeability is the same as plain concrete, which means when the pitch of steel bars is more than 15 cm, it is not affected by steel bars [18].

TABLE 1: The Result of experiment of permeability in vertical direction (unit: cm).

Classification	Concrete	D16@5	D16@7	D16@10	D16@15
R15	39	31	34	36	38
R31	45	37	40	42	45
S31	45	37	40	42	45

TABLE 2: The result of experiment of permeability in horizontal direction (unit: cm).

Classification	RF15	RF31	S31
Penetration depth	43	47	47

TABLE 3: Measurement of electric waves in plain concrete (unit: dBm).

Classification	10 cm	20 cm	30 cm	40 cm	50 cm	60 cm
R31	-47	-52	-64	-67	-71	-75

5.2. Permeability Experiment in Horizontal Direction. The result of permeability in horizontal direction is shown in Table 2. It was measured as 43 cm in R15, 47 cm in R31 and S31, and as the permeability experiment in vertical direction, R31 and S31 with big intensity showed better permeability. Besides, when compared with the permeability experiment in vertical direction, the permeability in horizontal direction was deeper. This suggests effects of the direction by radiation pattern of antenna attached to module and Chip antenna shows similar radiation pattern with monopole antenna that is an omnidirectional one (shown as Figure 15) and it is also similar with the radiation pattern of the existing small antenna. What is a solid line is the exact radiation pattern and from a view of this radiation pattern, the reason of resulting in minutely deeper penetration in horizontal direction than vertical direction is that when the permeability experiment in horizontal direction was conducted, the part of sensors was laid on the right side with piling up concrete on the left side, which was confirmed with about 5 ~ 8 variance when the radiation pattern from the left side was compared with upwards radiation pattern in radiation pattern (Figure 15) [19].

5.3. Analysis Using Spectrum Analyzer. As a measurement result of attenuation of electric waves using Spectrum Analyzer, it showed -27 dBm in free space. In addition, as shown in Table 3 as concrete is getting thicker the loss value of electric waves was definitely disclosed in plain concrete with -47 dBm in the thickness of 10 cm, -64 dBm in 30 cm, and -71 dBm in 50 cm. It was considered that the electric waves were scarcely transmitted as -75 dBm in concrete thickness of 60 cm. From the result of experiment it was suggested that wireless communication of module was possible up to 45 cm.

Besides, Table 4, showed -60 dBm in D16@5 that has the pitch of 5 cm, -56 dBm in D16@7, -51 dBm in D16@10, and -50 dBm in D16@15 in reinforced concrete. From these results, it could be seen that the closer the pitch of steel bars is the more attenuation of electric waves happens. Furthermore,

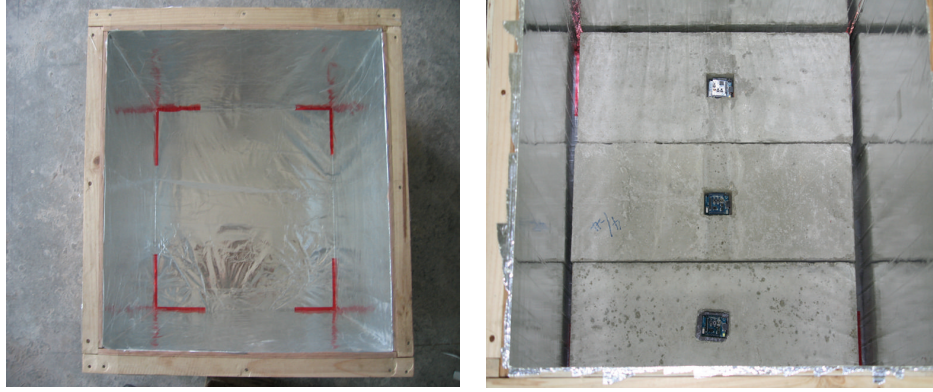


FIGURE 10: Left plates: Aluminum special case, right plates: base plate.

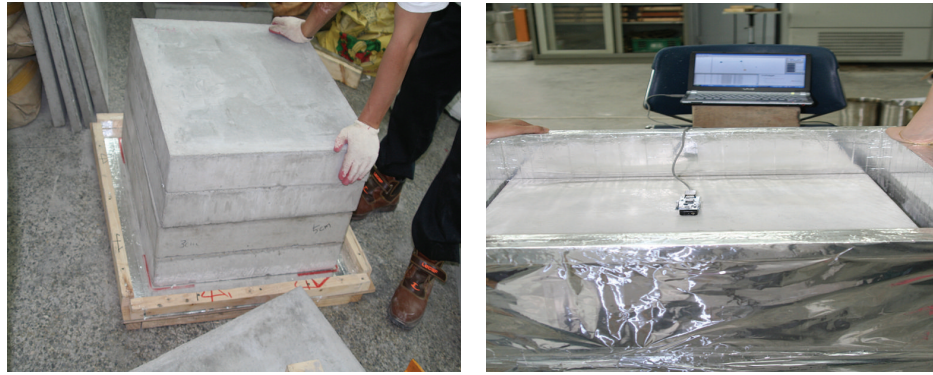


FIGURE 11: Permeability experiment in vertical direction.

TABLE 4: Measurement of intensity of electric waves in reinforced concrete (unit: dBm).

Classification	D16@5	D16@7	D16@10	D16@15
R31	-60	-56	-51	-50

there was -4 dBm attenuation of electric waves in the pitch between 7 cm and 10 cm. Finally they show that they are affected a little by steel bars up to 10 cm and from the fact that there is no big change in 15 cm, the Pitch of 15 cm affects penetration of electric waves as shown in the permeability experiment above (Figure 16).

5.4. Analysis by the Length of Wavelength of Frequency. The signal received in antenna with wireless communication module is generally affected by the length of wavelength of frequency for smooth communication. Frequency is how many oscillations for 1 second occur. As shown in Figure 17 if one oscillation happens per one second, it is called 1 Hz and one cycle is shown as \sim , which is considered to oscillate one time. In addition, the wavelength means the distance of a single oscillation. In other words, the length of one cycle is wavelength [20]:

$$\begin{aligned} \text{Oscillation velocity of a single time (m/s)} &= 3.0 \times 10^8 \\ (\text{m/s})/2.4 (\text{number}) \times 10^8 (\text{number}) &= 0.125 (\text{m/s}). \end{aligned}$$

$$\begin{aligned} \text{Oscillation distance of a single time (m)} &= 0.125 (\text{m/s}) \\ \times 1 (\text{s}) &= 0.125 (\text{m}). \end{aligned}$$

The frequency band used in this experiment is 2.4 GHz that oscillates 2.4×10^8 times for one second. In other words, the velocity of electric waves (the velocity of light) per one second should be divided by the times per one second 2.4 GHz oscillates to get the oscillation distance of one time. If the velocity of one time 2.4 GHz oscillation were calculated, oscillation distance of one time could be obtained by multiplying it by the time. The velocity of electric waves for one second is 3.0×10^8 (m/s) and the oscillation frequency of frequency for one second is 2.4×10^8 . In other words, the oscillation velocity of one time is 0.125 m/s and the oscillation distance of one time is 12.5 cm by 0.125 m/s. Besides the absorption of electric waves of Chip antenna occurs in a conductor less than one wavelength (λ). Namely, the absorption of electric waves happens in the wavelength more than 12.5 cm. The result of experiment was analyzed by this.

In case that the pitch of steel bars both in perpendicular and diagonal directions is within λ as in Figure 18, since the maximum length that electric waves can go through becomes less than λ , steel bar which is a conductor absorbs electric waves [21].

Finally, it is determined that in reinforced concrete with the pitches of 5 cm and 7 cm that are less than 12.5 cm (λ), steel bars absorb so much electric waves of wireless

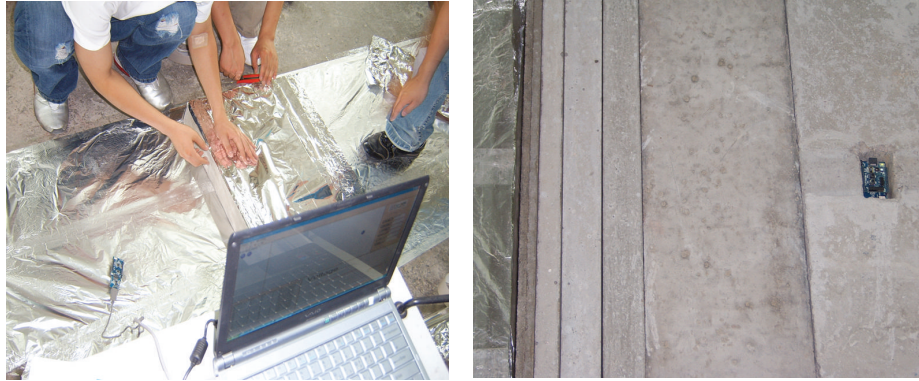


FIGURE 12: Permeability experiment in horizontal direction.

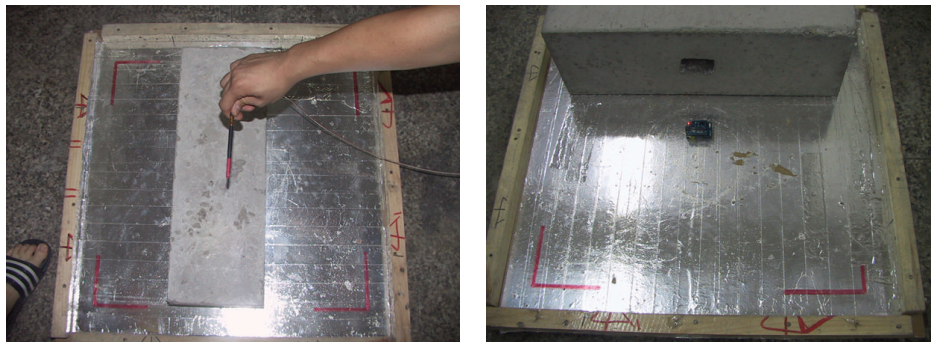


FIGURE 13: Experiment of measurement of electric waves attenuation.

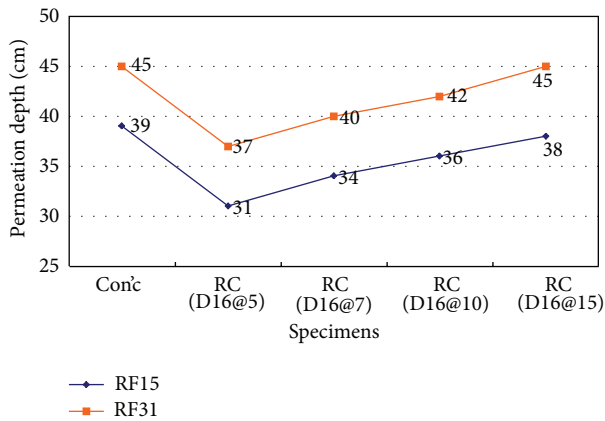


FIGURE 14: The result of experiment of permeability in vertical direction (unit: cm).

communication that takes place on communication barrier. Besides, reinforced concrete with the pitch of 10 cm is affected in perpendicular direction by the absorption of electric waves but in case of diagonal direction, the distance is 14.14 cm which is longer than 12.5 cm (λ) which showed that it was not affected. It is considered that reinforced concrete with the pitch of 15 cm is not affected by steel bars during wireless communication since it is more than 12.5 cm (λ) in both

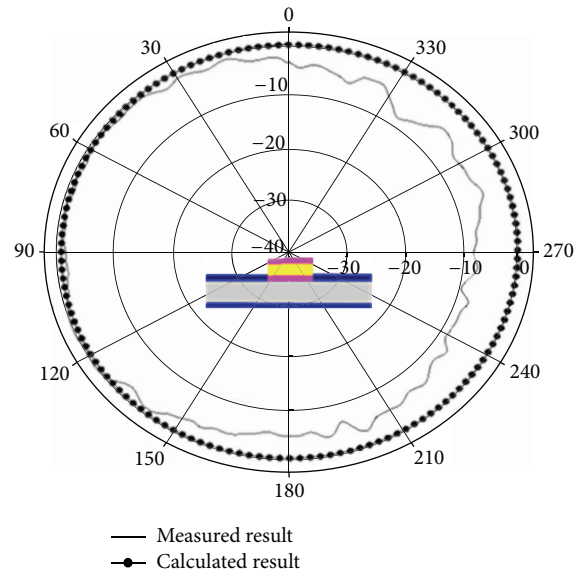


FIGURE 15: Radiation pattern of Chip antenna.

perpendicular and diagonal directions. These results agree with experiment of permeability depth and analysis results of attenuation of electric waves of Spectrum Analyzer.

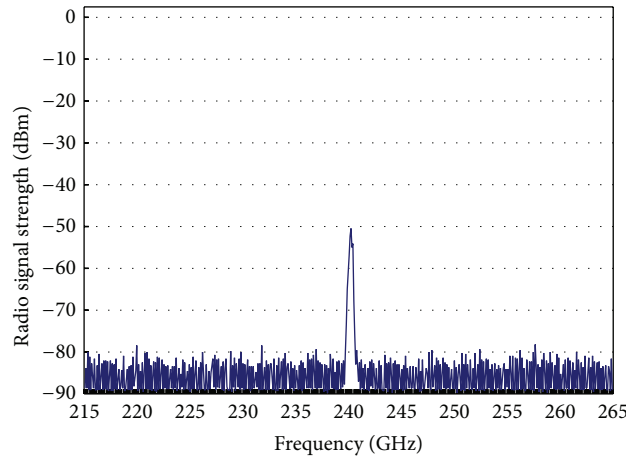


FIGURE 16: Spectrum of concrete with the thickness of 20 cm.

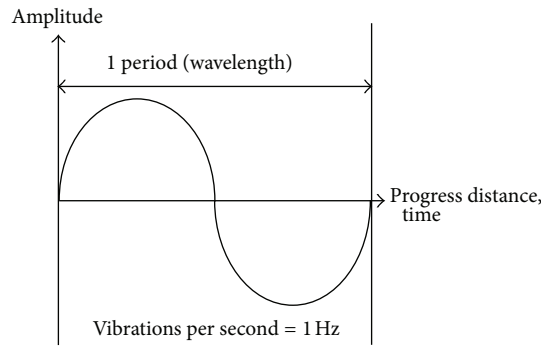


FIGURE 17: The concept of frequency.

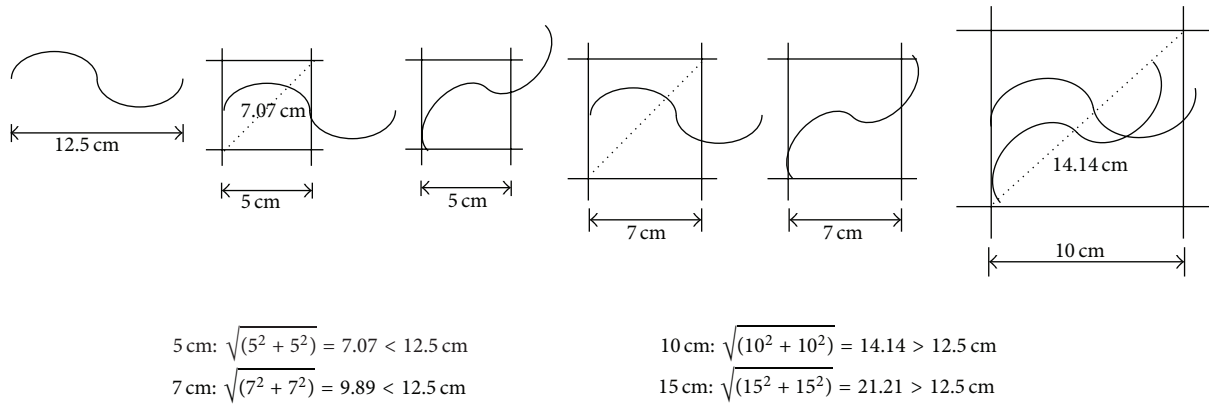


FIGURE 18: The analysis of wavelength of frequency.

6. Conclusion

The test of capability of wireless communication of sensor node embedded in reinforced concrete structure was conducted to apply new Ubiquitous Computing techniques and networking techniques to construction industry in this experiment and the results are as below.

- (1) When the test of transmission and reception in free space was implemented using transmission and reception module of wireless communication it showed more than 200 m for the possible distance of wireless communication. This shows that wireless communication module can be used with attachment to bridges or the outside structure.

- (2) As a result of measurement of distance of wireless communication in vertical and horizontal directions in plain concrete it penetrated 45 cm in vertical direction and 47 cm in horizontal direction. These results seem to be possibly criteria when wireless communication module is embedded in civil and architectural structures.
- (3) The fact that the horizontal permeability was deeper in permeability experiment of plain concrete in vertical/horizontal direction suggests that it penetrates better since the pattern of antenna shows higher value in the horizontal direction than in the vertical direction with influence of direction of antenna pattern of module used in this experiment.
- (4) As a result of experiment of attenuation of electric waves in wireless communication through spectrum of reinforced concrete when the pitch of steel bars was 5 cm, it showed -60 dBm, -51 dBm for 10 cm, and -50 dBm for 15 cm. It showed attenuation of electric waves by 1 dBm between the pitches of 15 cm and 10 cm, 4 dBm between 10 cm and 7 cm, and 4 dBm between 7 cm and 5 cm. Finally, the narrower the pitch of steel bars was, the more attenuation of electric bars occurred, and this result indicated that steel bars affect wireless communication.
- (5) It was considered that the phenomenon of attenuation did not occur since attenuation of -1 dBm between the pitches of 10 cm and 15 cm of steel bars was a delicate difference. Despite this result, when wireless is applied to inside structure, if the pitch of steel bars is 10 cm, it is not affected by steel bars.
- (6) Since the absorption of electric waves of Chip antenna with 2.4 GHz frequency occurs in a conductor with wavelength more than 12.5 cm (λ), steel bars in reinforced concrete with the pitches of 5 cm and 7 cm absorb much electric waves in wireless communication, which impedes communication, and in case of 10 cm, the absorption of electric waves occurs in perpendicular direction not in diagonal direction. Besides, reinforced concrete with the pitch of 15 cm has more than 12.5 cm (λ), it is considered that it is not affected by steel bars in wireless communication.
- (7) The epitome of the above results is that it is possible to apply ubiquitous Active RF wireless transmission and reception to civil and architectural structures made of plain concrete and reinforced concrete.

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