Databased Fluctuating Wi-Fi Signal Simulation Environment for Evaluating the Control of Robots

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Robots were used at the site of the World Trade Center disaster, and they are being used to explore the interior of the Fukushima Daiichi Nuclear Plant (FDNP). Robots will be used at the FDNP for the next few decades, until the nuclear reactor is finally decommissioned. Wired communications systems have been used to teleoperate robots in hazardous areas where humans cannot work. In this paper, we show the fluctuation of Wi-Fi power strength in a real environment and that the fluctuations utilization is one of the key points to be considered while developing rescue robots for disaster-prone areas. We propose a simulation environment that simulates the fluctuation of the Wi-Fi power strength with a database and evaluates the performance of the robot with unstable Wi-Fi connectivity.

Keywords: response robot, rescue robot, robot test field, representation of databased radio-wave fluctuation, representation of unstable Wi-Fi connectivity

1. Introduction

Ever since the Great East Japan Earthquake of 2011, robots have been used to explore the interior of the Fukushima Daiichi Nuclear Plant (FDNP) and they will be used to perform a variety of tasks over the next several decades, until the nuclear facilities are finally decommissioned [1]. These tasks include clearing debris, monitoring the interiors and exteriors of buildings, setting up instruments, shielding and decontaminating, transporting materials, and constructing pipes and equipment. The robots will also be required to perform day-to-day activities; for example, monitoring the tanks used to store water that has been contaminated by radioactive materials [10,11].

It is assumed that the robots will be operated remotely to prevent accidents. With a wired connection, the trailing cable limits the range and movement of the robot. On the other hand, buildings, walls, furniture, or other objects act as obstacles to the propagation of a Wi-Fi signal. A hybrid system using both wired and wireless connections is a possible solution to these issues, and this approach was used to explore the buildings in the FDNP [12]. A Packbot pair was configured with one Packbot connected by a cable and acting as a wireless access point, while the second Packbot was operated wirelessly. To perform these operations, testing their behaviors that satisfy their mission in the FDNP is necessary [14].

In this paper, we propose a simulation environment that can reproduce realistic unstable Wi-Fi connectivity behavior, for evaluating response robots working in hazardous areas, by using the databased radio-wave power strengths measured at actual locations. This environment can also be used to conduct rehearsals for using the response robots in the areas with unstable Wi-Fi connectivity and where humans cannot enter and work.

Section 2 describes the environment where a response robot is used. Section 3 presents a fluctuation model and describes our proposed method for reproducing the fluctuations in the Wi-Fi signal and estimating the Wi-Fi connectivity in a given area. Section 4 describes two results of the proposed simulation: one is for the fluctuating Wi-Fi radio-wave strength similar to that in a normal environment and the other is for a similar situation in a disaster area. Section 5 discusses future areas for robot testing and concludes this paper.

2. Background and Related Works

Disaster situations require investigatory tasks to be undertaken by teleoperated robots rather than by human operators. When sensors and robots are newly developed for investigating buildings in disaster zones, testing the sensors and robots can help in verifying and improving their performance. Simulations have been used to shorten the development time and to check the functions of the sensors. Competitions, such as RoboCup Rescue, provide platforms on which the response robots and algorithms can be tested in the simulated environments of disaster zones where they are intended to operate [2–4].

Response robots are operated both indoors and outdoors in a disaster area and some robots are assumed to be teleoperated by Wi-Fi. Stable Wi-Fi connectivity is desired, however, as the strength of radio wave signals varies indoors and outdoors and fluctuates especially in the presence of large objects such as water tanks [10,11]. In the worst case, the robots that move outside the range of Wi-Fi signals cannot be controlled and may actually be lost. The following are required to test rescue robots: mobility at uneven areas, manipulating objects, sensing circumstances, and communication under unstable wireless conditions.

Calculating the signal strength requires the values of all reflected signal strengths that pass through that location and the influence of the fluctuation at a given location [5]. The calculation involves lapses in connectivity caused by unexpected objects

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(a) Measurement situation of Figs. 1(b) and (c).

(b) Strength of fluctuation caused by traffic at a crossing.

(c) Strength of fluctuation caused by people at a walking bridge.

Figure 1  Wi-Fi signal strength fluctuations measured outdoors depending on situations. The x-axis of graphs represents time in min:sec, and the y-axis represents the received radio-wave power in dB respectively.

3. Method for Reproducing Fluctuations in Radio-Wave Signal Strengths

3.1 Radio-Wave Signal Strength Fluctuations

3.1.1 Measured Fluctuations in Strength of Wi-Fi Signal Received Outdoors

Figure 1(a) shows the measurement situation of Figs. 1(b) and (c). Fig. 1(b) indicates the Wi-Fi signal strength at a crossing for approximately 15 minutes. The signal is interrupted by vehicle movement. Every five minutes, a traffic signal stops vehicles for two minutes. Table 1 shows the means and deviations of Wi-Fi signal strength for spans when traffic signals are on and off. Table 1 indicates that the number of vehicles does not cause the Wi-Fi signal strength to fluctuate.

Table 1  Means and deviations of outdoor Wi-Fi signal strength fluctuations caused by traffic.

| Time span | Mean [dB] | Deviation | Traffic |
|-----------|-----------|-----------|---------|
| A         | -57.9     | 2.4       | ON      |
| B         | -58.4     | 2.6       | OFF     |
| C         | -58.4     | 3.0       | ON      |
| D         | -59.4     | 2.5       | OFF     |
| E         | -57.4     | 2.5       | ON      |
| F         | -58.7     | 2.4       | OFF     |

Figure 1(c) shows the strength of Wi-Fi signals at a walking bridge. During the first four minutes, more than 10 people were moving around between the Wi-Fi access point and the Wi-Fi client. From the fourth minute to the sixth minute, very few people were moving around. Lastly, from the sixth minute to the fifteenth minute, several people were present. The three spans are represented as A, B, and C, respectively in Table 2.

Table 2 shows the means and deviations of signal strength at different periods. The Wi-Fi signal strength outdoor varies according to the number of people and fluctuations are caused.
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Figure 2(a) shows a small indoor corridor. A Wi-Fi transmitter is located at the left end, and a notebook PC acting as a Wi-Fi receiver is located at the right end. The dotted line indicates the route followed by the people. Fig. 2(b) presents the measured fluctuations in the strength of the Wi-Fi signal when it is interrupted by people moving around indoors. The x-axis of this graph corresponds to a duration of approximately 15 minutes.

Table 2 Means and deviations of outdoor Wi-Fi signal strength fluctuations caused by people.

| Time span | Mean [dB] | Deviation | Number of people |
|-----------|-----------|-----------|-----------------|
| A         | −62.2     | 2.5       | 10              |
| B         | −59.1     | 2.9       | 2 - 3           |
| C         | −60.0     | 2.2       | 4 - 6           |

Table 3 Means and deviations of indoor Wi-Fi signal strength fluctuations caused by people.

| Time span | Mean [dB] | Deviation | Number of people |
|-----------|-----------|-----------|-----------------|
| A         | −46.7     | 0.96      | 0               |
| B         | −47.9     | 1.7       | 1               |
| C         | −47.3     | 0.82      | 0               |

3.1.2 Measured Fluctuations in the Strength of Wi-Fi Signal Measured Indoors

Figure 2(a) shows a small indoor corridor. A Wi-Fi transmitter is located at the left end, and a notebook PC acting as a Wi-Fi receiver is located at the right end. The dotted line indicates the route followed by the people. Fig. 2(b) presents the measured fluctuations in the strength of the Wi-Fi signal when it is interrupted by people moving around indoors. The x-axis of this graph corresponds to a duration of approximately 15 minutes.

Table 3 lists the means and deviations of the signal strength and shows that the fluctuation caused by people indoor is smaller than the fluctuation in the Wi-Fi signal strength outdoor.

3.1.3 Discussion on Fluctuating Wi-Fi Signal Strengths Outdoors and Indoors

From Tables 1, 2, and 3, we infer the following:

1. The constant fluctuation at a given location depends on the surrounding environment, such as outdoor/indoor, and the number of people around.
2. The constant fluctuation is not influenced by movement of people or vehicles.

Thus, the width of the constant fluctuation in the signal strength depends on the surrounding environment.

3.2 A Databased Simulation Environment for Fluctuations in the Signal Strength

The fluctuations in the signals depend on the situations. Many methods have been proposed to calculate the strength of radio-wave signals [5]. We propose the following databased Wi-Fi signal simulation environment.

Algorithm 1: Algorithm for calculating fluctuating Wi-Fi power strength.
Algorithm 1 is a flow to calculate fluctuation of the Wi-Fi power strength between Wi-Fi access points and robots. This method of calculating the fluctuations simulates the fluctuations in the power of the radio waves and determines whether the wireless communication status is “connected” or “disconnected,” even in cases involving combinations of open spaces, buildings, and narrow corridors within buildings, as in the FDNP [13]. In homes, offices, factories, schools, or disaster areas, there are many locations where fluctuations can occur, both indoors and outdoors.

### 3.3 Modeling the Fluctuations in Signal Strength

Equation (1) is proposed to simulate the fluctuation of the radio-wave power in Step 4 of Algorithm 1.


g(t) = a_1 \sin \left( \frac{2\pi t}{t_1} \right)
+ a_2 \sin \left( \frac{2\pi t}{t_2} \right)
- a_3 \text{Rand} \left( |\sin \left( \frac{2\pi t}{t_3} \right)|^p \right)
- a_4 p

Equation (1) describes three waves.

- $a_1$ is the width of the radio-wave fluctuation power spectrum, and $t_1$ is the length of the cycle of the radio-wave fluctuation power.
- $a_2$ is the width of the radio-wave noise power spectrum, and $t_2$ is the length of the cycle of the radio-wave noise power.
- $a_3$ is the width of the strength of the radio-wave peak noise power, $\text{Rand}$ is a random number between 0 to 1 in the normal distribution, $t_3$ is the length of the cycle of the radio-wave peak noise power, and $p$ is a multiplier used for producing a peak.
- $a_4$ represents the decreasing radio-wave power caused by people walking. $a$ is 1 when people are around the path and 0 otherwise.

### 4. Simulation Results

#### 4.1 Simulation Results of Fluctuating Wi-Fi Radio Waves

We experimented to demonstrate the capability of our proposed method for reproducing fluctuation phenomena by using databased fluctuation parameters. To calculate $S_{ij}$, the Friis free-space path loss equation was used [7]. To calculate diffraction, a knife-edge diffraction model was used [5, 9]. The method can calculate the strength with diffraction effect and $-92$ dB is used to threshold $FS_{ij}$. Table 4 presents the database of fluctuation parameters. The second, third, and fourth columns of the table correspond to Figs. 1(b), (c), and 2 respectively. The three situations correspond to the environments: outdoor with vehicles, outdoor with people and indoor with people. Table 4 is a start-up database. To calculate $F_{ij}$ in an environment, one can select a similar situation from the database and use the parameters related to the situation.

The parameters in the database are used to calculate the Wi-Fi radio-wave signal strength. Fig. 3 shows the results of a simulation of the fluctuations for 15 minutes that occur indoors and outdoors. The continuous line in each graph indicates the simulated values of the fluctuations in the signal strength. The dotted line shows the measured signal strength. The continuous line is similar to the dotted line. As the tables in the right column of Figs. 3(a), (b), and (c) show, the means and deviations of the three curves are also similar to the measured values.

#### 4.2 Simulation Experiments in a Similar Real Situation

We made a simulation field that is similar to an array of tanks in the FDNP [13]. Fig. 4(a) is an image of a real tank array at the FDNP. There are some shadow areas of Wi-Fi radio waves in the tank array. Fig. 4(b) shows a top view of the environment of this experiment that simplifies the tanks in the FDNP. Four black boxes indicate a tank array, and the small white point on the left is the Wi-Fi access point. The size of each box tank is 10 m by 10 m. The tanks are separated by 5 m width corridors. The distance between the Wi-Fi access point and the left bottom tank is 90 m. The brightness of the pixels corresponds to the strength of the received signal at a given point. The area is a mesh with a resolution of 0.1 m by 0.1 m and Wi-Fi radio-wave strength is calculated for each mesh. Black pixels correspond to a received signal strength of less than $-92$ dB, in which case the Wi-Fi signal will be disconnected.

We experimented in three situations for radio-wave power strength (Table 5).

**Case 1**: The simulated Wi-Fi radio-wave power strength was calculated with only attenuation.

**Case 2**: The simulated Wi-Fi radio-wave power strength was calculated with diffraction.

**Case 3**: The simulated Wi-Fi radio-wave power strength was calculated with fluctuation in a situation of weak radio-wave power strength.

Figure 4(b) is the result of Case 1. Response robots should be tested in such unstable Wi-Fi radio-wave strength environments as Case 3, but not Case 1.

#### 4.2.1 Discussion of Fluctuations in the Strength of Radio-Wave Power

We divided a shadow area of radio wave in Fig. 4(b) into sixteen segments. In Fig. 5, the sixteen segments are named A to P between two boxes. The dimension of each segment from A to O is 1 m by 1 m, and that of Segment P is 5 m by 7 m, respectively. The gray line in Fig. 5 is a boundary of whether a point can see Wi-Fi access point directly or not.

Table 6 shows the means and deviations of the Wi-Fi radio-power strength at the center of each segment from A to P. The mean and deviation of Wi-Fi power strength are calculated from 10 minutes simulated Wi-Fi radio-wave strength at the place. For Case 1 of Table 6, at only Segment C, D, and E, the Wi-Fi access point could be seen directly, and the Wi-Fi radio wave was received. Case 2: Segment B received a connectable Wi-Fi radio-
Table 4  Databased parameters for various places and scenarios.

| Parameters | Outdoor | Indoor |
|------------|---------|--------|
|            | With vehicles | With walking people | With walking people |
| $a_1$ [dB] | 2       | 2      | 1      |
| $t_1$ [sec] | 180     | 200    | 1200   |
| $a_2$ [dB] | 3       | 2      | 0.5    |
| $t_2$ [sec] | 30      | 30     | 30     |
| $a_3$ [dB] | 20      | 20     | 6      |
| $t_3$ [sec] | 120     | 120    | 180    |
| $p$        | 10000   | 10000  | 10000  |
| $a_4$ [dB] | 0       | 5      | 3      |

(a) Outdoors with vehicles moving between the Wi-Fi access point and the Wi-Fi client.

(b) Outdoors with people moving between the Wi-Fi access point and the Wi-Fi client.

(c) Indoors with people moving between the Wi-Fi access point and the Wi-Fi client.

Fig. 3  Simulated fluctuations in Wi-Fi signal strength for comparison of situations with means and deviations. Continuous lines correspond to simulated values; dotted lines indicate actual measured Wi-Fi signal strengths. The x-axis represents time in min:sec, and the y-axis represents the received radio-wave power in dB.

Table 5  Three cases of Wi-Fi radio-wave situations.

| Situation | Fluctuation | Diffraction |
|-----------|-------------|-------------|
| Case 1    | OFF         | OFF         |
| Case 2    | OFF         | ON          |
| Case 3    | ON          | ON          |

wave strength by diffraction. Case 3: Segments B and J received a sometimes connectable Wi-Fi radio-wave strength by fluctuation. At Segment B, the minimum Wi-Fi radio-wave strength was $-93$ dB. At Segment J, the maximum Wi-Fi radio-wave strength was $-89$ dB.

4.2.2 Measurements in Real World

Our proposed method can provide a robot simulation platform with unstable Wi-Fi connection. For validating the simulated fluctuation of signal power strengths, some real Wi-Fi radio-wave power strength was measured at a place similar to that in Fig. 5.
Table 6  Statistics of simulated Wi-Fi radio-power strength in Segment A-P with Case 1, 2, and 3.

| Segment | Case 1 | Case 2 | Case 3 |
|---------|--------|--------|--------|
|         | Mean [dB] | Deviation | Wi-Fi connection | Mean [dB] | Deviation | Wi-Fi connection | Mean [dB] | Deviation | Wi-Fi connection |
| A       | NRW     | -       | None       | -100     | 0.0       | None       | -101     | 2.6       | None       |
| B       | NRW     | -       | None       | -87.5    | 0.0       | Always     | -88.1    | 2.6       | Sometimes  |
| C       | -79.8   | 0.0     | Always     | -79.8    | 0.0       | Always     | -80.3    | 2.6       | Always     |
| D       | -79.8   | 0.0     | Always     | -79.8    | 0.0       | Always     | -80.4    | 2.6       | Always     |
| E       | -79.9   | 0.0     | Always     | -79.9    | 0.0       | Always     | -80.4    | 2.6       | Always     |
| F       | NRW     | -       | None       | -109     | 0.0       | None       | -110     | 2.6       | None       |
| G       | NRW     | -       | None       | -116     | 0.0       | None       | -133     | 2.6       | None       |
| H       | NRW     | -       | None       | -102     | 0.0       | None       | -103     | 2.6       | None       |
| I       | NRW     | -       | None       | -98.1    | 0.0       | None       | -98.7    | 2.6       | None       |
| J       | NRW     | -       | None       | -93.2    | 0.0       | None       | -93.7    | 2.6       | Sometimes  |
| K       | NRW     | -       | None       | -112     | 0.0       | None       | -113     | 2.6       | None       |
| L       | NRW     | -       | None       | -111     | 0.0       | None       | -111     | 2.6       | None       |
| M       | NRW     | -       | None       | -108     | 0.0       | None       | -109     | 2.6       | None       |
| N       | NRW     | -       | None       | -106     | 0.0       | None       | -107     | 2.6       | None       |
| O       | NRW     | -       | None       | -104     | 0.0       | None       | -105     | 2.6       | None       |
| P       | NRW     | -       | None       | -116     | 0.0       | None       | -116     | 2.6       | None       |

NRW: No radio wave (the radio-wave receiver cannot see the Wi-Fi access point directly)

Table 7  Means and deviations of the measured three real places for validation.

| Place | Mean [dB] | Deviation | Wi-Fi connectivity |
|-------|-----------|-----------|--------------------|
| WC1   | -101      | 5.2       | None               |
| WC2   | -97.2     | 6.0       | Sometimes          |
| WC3   | -64.7     | 3.8       | Always             |

Fig. 6(a) shows the place used for measurement. Fig. 6(b) shows the positions of a Wi-Fi access point, and three measured points—WC1, WC2, WC3—that correspond to A, B, C respectively in Fig. 5. There is a building instead of the left box in Fig. 5 that made a shadow place of Wi-Fi radio-wave. A Wi-Fi access point was located at 100 m on the left of the building edge. WC1, WC2, and WC3 were located at a distance of 1 m, 2 m, 4 m on the right of the building edge respectively.

The Wi-Fi radio-wave signal strength of the three points was measured during an hour simultaneously. The Wi-Fi radio-wave
signal strengths were measured per second and the means and deviations of the measurement results are shown in Table 7. At WC1, the signal strength of the Wi-Fi radio-wave was not connectable level. The mean value at WC2 was not connectable level, however the deviation was so large that it was connected at sometime and the other time, it was not connected. At WC3, it was connected all times. Measurements in real environment show that the three types of connections—no connection, sometimes connection and always connected—occurred in the real situations.

5. Discussion and Summary

The performance for the response robot should be tested before response robots can be used at the spot. Targets include training the operators, enhancing robot mobility, and undertaking tasks after disasters indoors and outdoors [6, 8]. A realistic wireless communication simulator considering the effects of fluctuations and diffraction in Wi-Fi signals will be essential for simulating the environments in which robots operate. The investigation of the tanks in the FDNP is an example.

In this paper, we proposed a simulation method for reproducing the fluctuations in radio waves, using the radio-wave power strength from a database of the measured actual radio-wave power strengths. We performed two experiments to demonstrate the effectiveness of our method. The first revealed that our radio-wave fluctuation simulation closely matched the actual fluctuation behavior. The second experiment showed that our simulation of the simultaneous fluctuation and diffraction of the Wi-Fi signal behavior resembled the actual signal behavior.

Our proposed evaluation method for addressing actual Wi-Fi problems is expected to be useful for evaluating the performance of existing and new response robots, robot behavior algorithms, operators, and rescue strategies. The experiments show that our proposed Wi-Fi test field considering the fluctuations of Wi-Fi signals can evaluate the response robots intended for use in disaster zones before they are actually deployed. By increasing the number of measurements of Wi-Fi situations and corresponding environments, our method will provide a simulation environment for testing robot operations. We believe that our method will be able to check robot operations in disastrous environments.

References

[1] H. Asama. Robot & remote-controlled machine technology for response against accident of nuclear power and toward their decommission. 2012.
[2] USARSim: a RoboCup virtual urban search and rescue competition. volume 6561, 2007.
[3] S. Balakirsky, S. Carpin, A. Kleiner, M. Lewis, A. Visser, J. Wang, and V. A. Ziparo. Towards heterogeneous robot teams for disaster mitigation: Results and performance metrics from robocup rescue. J. Field Robotics, 24(11-12): 943–967, 2007.
[4] H. L. Akin, N. Ito, A. Jacoff, A. Kleiner, J. Pellenz, and A. Visser. Robocup rescue robot and simulation leagues. The AI Magazine, 34(1), 2013.
[5] Y. Hosoya. Radiowave propagation handbook (In Japanese). Re-alize Science & Engineering Center Co.,Ltd, Tokyo, Japan, 1999.
[6] S. Okamoto, K. Kurose, S. Saga, K. Ohno, and S. Tadokoro. Validation of simulated robots with realistically modeled dimensions and mass in usarsim. In Safety, Security and Rescue Robotics, 2008. SSRR 2008. IEEE International Workshop on, pp. 77–82, Oct. 2008.
[7] J. A. Shaw. Radiometry and the friis transmission equation. American Journal of Physics, 81(1): 33–37, 2013.
[8] M. Shimizu and T. Takahashi. Training platform for rescue robot operation and pair operations of multi-robots. Advanced Robotics, 27(5): 385–391, Mar. 2013.
[9] M. Shimizu and T. Takahashi. Simulated environment for wirelessly controlled robots using the natural behavior of radio waves. In Safety, Security, and Rescue Robotics (SSRR), 2014 IEEE International Symposium on, pp. 1–6, Oct. 2014.
[10] E. Strickland. Dismantling fukushima: The world’s toughest demolition project. Technical report, http://spectrum. ieee.org/energy/nuclear/dismantling-fukushima-the-worlds-toughest-demolition-project, IEEE Spectr., Feb. 2014.
[11] E. Strickland. Fukushima’s next 40 years. Spectrum, IEEE, 51(3): 46–53, Mar. 2014.
[12] Tokyo Electric Power Company. Investigation on the operating floor of the reactor building of unit 2 fukushima dai-ichi nps. http://www.tepco.co.jp/en/nu/fukushima-np/roadmap/images/m120227_98-e.pdf, Feb. 2012.
[13] Tokyo Electric Power Company. Water leak at a tank in the h4 area in fukushima daiichi nuclear power station (follow-up information). http://www.tepco.co.jp/en/nu/fukushima-np/handouts/2013/images/handouts_130820_03-e.pdf, Aug. 2013.
[14] Tokyo Electric Power Company. Mid-and-long-term roadmap towards the decommissioning of fukushima daiichi nuclear power units 1-4. http://www.tepco.co.jp/en/nu/fukushima-np/roadmap/conference-e.html, date:26 Jun. 2013.

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