Feasibility Evaluation on an Instant Invader Detection System with Ultrasonic Sensors Scattered on the Ground

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***Abstract*—Increasing interest in security demands privacy-aware security systems, which do not use camera, especially for personal home security. As a candidate for this purpose, this paper presents an instant invader detection system that finds an invader by using small sensor nodes distributed on the ground. Once a sensor node detects a suspicious phenomenon, this information is wirelessly transmitted to the base in the house. This paper, as a first step, evaluates the feasibility of the proposed system in terms of invader detection accuracy and system lifetime. We firstly investigate what sensor can be used and how the sensor should be used for the human detection. Then, for evaluating the proportion of invader detection and necessary energy for sensor nodes, we perform simulations that are based on the measured characteristics of ultrasonic sensors placed on the ground. Experimental results show that the proposed system can attain 99% invader detection while the sensor nodes can survive with a button cell for four years. In addition, this performance can be obtained even with the sensors randomly scattered on the ground, which could contribute to the instant installation of the proposed system.**

I. Introduction

Security system is now being introduced not only to public space and office but also home. Current outdoor security systems for home are mostly based on surveillance camera, and then privacy invasion is a serious concern that prevents the home security system from being introduced. Other outdoor security systems without camera use laser sensor and optical fiber for surveillance and detection of invader to railroad. Installation of these systems needs expensive engineering work and is not suitable for instant home security purpose.

This paper investigates the feasibility of an invader detection system that does not use camera for privacy preservation but instead use small sensors scattered on the ground. Scattering the sensors is easy to do and cheap sensors might be adequate for this system, which could result in a cost effective solution. However, it is not clear whether such sensors scattered on the ground can detect invaders. Therefore in this paper, we first investigate sensing methods with radio wave and ultrasonic wave and identify a possible sensing method. We then evaluate the feasibility of the system in terms of proportion of invader detection, system lifetime and installation instantness.

The rest of this paper is organized as follows. Section II discusses the requirements for this system and evaluation metrics. Section III experimentally investigates sensing methods suitable for invader detection. The feasibility of the system with ultrasonic sensors is evaluated through simulation in Section IV, and concluding remarks are given in Section V.

II. Proposed Invader Detection System

This section first describes the requirements for the invader detection system of our interest and presents a system that could satisfy the requirements.

The invader detection system tailored for instant outdoor home security has the following requirements.

- Not use camera image for privacy preservation.
- Attain high proportion of invader detection for higher security.
- Achieve easier installation.
- Sustain the system for years without maintenance.

For easier installation, professional electrical engineering work should be avoided. Especially in the outdoor, power outlet becomes a problem for installation, and hence battery-powered system is desirable. However, in this case, the power consumption of the system could become an obstacle for keeping the system active for years without maintenance.

We thus made a proposal below as a system that may satisfy the above requirements. Figure 1 illustrates the proposed system that scatters small sensor nodes in the area for the invader detection. The sensor nodes include sensor, battery and wireless transceiver. The power consumption of the sensor node is low enough to make the node alive for years without battery replacement or forever with solar cell. The sensor nodes perform sensing for invader detection periodically, and a suspicious event is informed to the base in the house wirelessly. Conventional invader detection systems focus on the boundary of the area for surveillance while the proposed system watches the entire area, which could improve the proportion of invader detection or enable the usage of cheaper sensors. The sensing methods suitable for this system will be discussed in Section III.

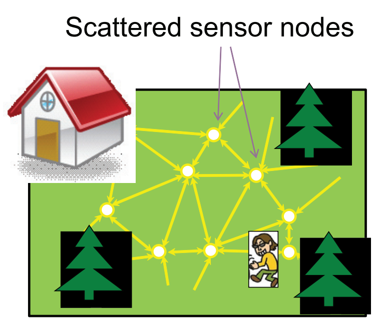


Fig. 1. Proposed system for invader detection for instant home security.

To evaluate the feasibility of the proposed system, three primary metrics should be considered. The first metric is the proportion of invader detection, and a higher value is desirable. As a security system, high missing rate of the invader detection is not acceptable. This proportion of invader detection depends on the temporal interval of sensing at each node and the spatial density of the scattered nodes. On the other hand, shorter interval of sensing increases power consumption of the sensor node and could reduce the system lifetime. Also, denser scattering increases the system cost.

The second metric is the system lifetime. The system lifetime depends on the power consumption and the battery capacity of the node. Here, for unaware sensing, smaller volume of the sensor node is desirable, which limits the battery capacity. On the other hand, as mentioned above, there is a trade-off between power consumption and proportion of invader detection in general, and this trade-off needs to be investigated.

The third metric is the instantness of system installation. The most effort of the system installation is to place the sensor nodes on the ground. If the many sensor nodes need to be placed regularly, the installation requires a laborious task. On the other hand, if scattering the nodes is enough for invader detection, the installation becomes easier. In addition, a smaller number of sensor nodes make the installation easier and reduce the system cost.

III. Preliminary Sensor Evaluation

In the proposed system, the sensor nodes on the ground need to be capable of human detection. This section reports the results of preliminary experiments exploring sensing methods suitable for the proposed system. We here take radio wave and ultrasonic wave as a means of human detection and evaluate their feasibilities. Infrared is another possible means, and passive infrared (PIR) sensor, which detects the temperature difference between background temperature and human temperature, is often used. However, this PIR sensor is not suitable for outside under strong sunlight, especially in summer. Due to this, the invader detection system reported in [1] and the human tracking systems in [2], [3] supposed the interior of a building. Hence, infrared was not evaluated in this paper.

A. Radio wave

This subsection discusses the feasibility of human detection with radio wave. We focus on the shielding effect due to human body, and the magnitude variation of the radio wave was evaluated. Note that disturbance of the radio wave is used for invader detection in [4], but in the outside the magnitude of radio wave is fluctuating, and hence this approach was not evaluated here.

We put a pair of helical antennas on the ground and evaluated forward transmission coefficient S21 with a network analyzer. The placement configurations are as follows. A pair of antennas were put on the ground in a building where the ceiling height was 2.7 m. The distance between them was 30 cm, 50cm or 100cm. A human was standing at the center between the antennas. Note that a part of the experiments shown in this subsection were performed outside and the same tendencies were observed. We tested two types of antennas; 315MHz (ANT-315-CW-RH, Antenna Factor) and 2.4GHz frequencies (ANT-24G-HL90-SMA, R.F. Solutions Ltd.).

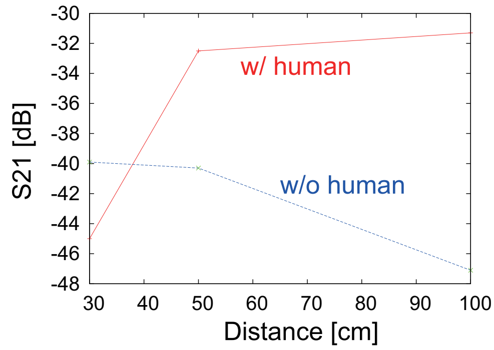


Fig. 2. S21 of radio wave with and without human at 315 MHz.

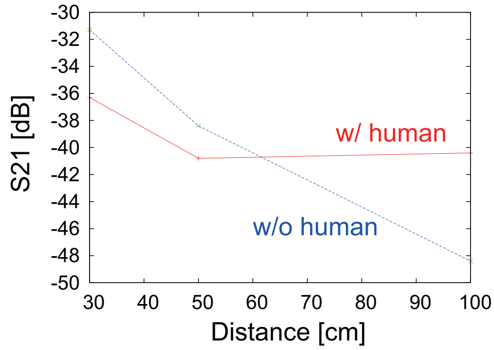
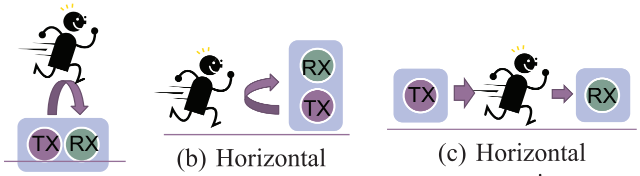


Fig. 3. S21 of radio wave with and without human at 2.4 GHz.

Figures 2 and 3 show S21 of radio wave with and without human at 315 MHz and 2.4 GHz, respectively. Without human, S21 decreases as the distance between transmitter (TX) and receiver (RX) antennas increases. On the other hand, S21 varies due to the existence of human, and the magnitude variation can be positive and negative. It seemed that the radio wave could be used for human detection. Besides, this variation originates from the fading [5] instead of simple shielding effect, and the existence of human generates or diminishes the multi-paths of the radio wave propagation. This multi-path propagation can change due to automotive passing and parking in the adjacent area. In addition, such frequencies used for experiments are often used for other purpose, and the amplitude fluctuates due to, for example, wireless LAN. Thus, the magnitude variation due to invader is less predictable and hence radio based human detection is less reliable.

B. Ultrasonic Wave

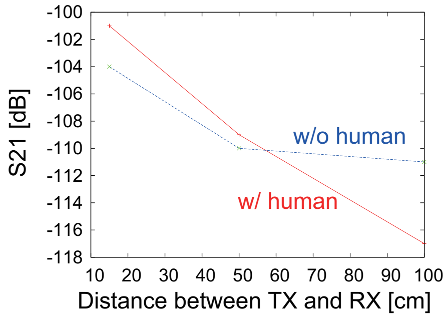
Ultrasonic wave sensor is usually used to detect the existence of an object or measure the distance to the object by transmitting ultrasonic wave from TX and receiving the



(a) Vertical reflection (b) Horizontal reflection (c) Horizontal attenuation

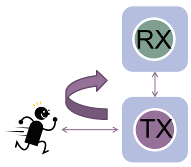
Fig. 4. Sensing methods using ultrasonic wave.

(a) Human setup.

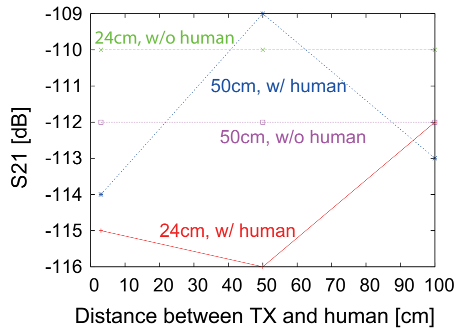


(b) Measured S21.

Fig. 5. Experiments for vertical reflection.



(a) TX and RX setup.



(b) Measured S21.

Fig. 6. Experiments for horizontal reflection.

reflected or attenuated wave with RX. Let us show some application examples of ultrasonic wave sensors. Nishida et al. developed an ultrasonic tagging system for observing human activity [6]. In this system, a human has an ultrasonic transmitter with a unique ID, and three-dimensional motion activity is reconstructed based on the received ultrasonic wave. Hori et al. reported a system for nursing care support that detects the patient existence using the ultrasonic sensors equipped on the hospital ceiling [7]. Kim et al. developed a mobile security robot and ultrasonic sensor is used to find and avoid obstacles [8].

When ultrasonic sensors are used for the proposed invader detection system, we have three candidates of the sensing methods shown in Fig. 4. The first method transmits ultrasonic wave vertically and receives the reflected wave for human detection, as illustrated in Fig. 4 (a). When a human exists over the sensor, the magnitude of the received signal is expected to become larger. The second method transmits ultrasonic wave horizontally, and receives the wave reflected by a human, as shown in Fig. 4 (b). Similar to the first method, the received signal becomes stronger when a human exists. The third method transmits ultrasonic wave horizontally and receives the attenuated wave like Fig. 4 (c). The attenuation becomes significant and the received signal is expected to be weak when a human exits between TX and RX.

We experimentally evaluate the feasibilities of the above three sensing methods for the proposed system. We used a pair of ultrasonic transmitter (MA40S4S, Murata Manufacturing, Co. Ltd.) and ultrasonic receiver (MA40S4R, Murata Manufacturing, Co. Ltd.) for the experiments, and each sensor was driven through a 50 Ohm resistor. These TX and RX have a directivity of 80 degree. 40 kHz signal was used for the measurement.

1) Vertical reflection: The sensors were placed facing upward on the ground, and the horizontal distance between them was 15, 50 or 100cm. We evaluated S21 using a network analyzer with and without human, where the human was standing whose shoe was over the transmitter as shown in Fig. 5 (a).

Figure 5 (b) shows the measured S21. When there was not a human, the received signal was smaller than -100 dB as expected. However, even when there was a human, the received signal was smaller than -100 dB, which means the reflected signal was very weak. Thus, the vertical reflection cannot be used for human detection.

2) Horizontal reflection: We placed TX and RX horizontally facing to the human. The distance between transceiver and receiver was set to 24 or 50cm, and the distance between TX and the human was varied to 3, 50 and 100cm, as illustrated in Fig. 6 (a). The human was standing facing to TX.

The measured S21 is shown in Fig. 6 (b). Similar to vertical reflection, disregarding the existence of human, the received signal was below -100 dB. The reflected signal was too weak for human detection, and the horizontal reflection cannot be used for the proposed system.

3) Horizontal attenuation: The TX and RX were placed horizontally facing to each other on the ground, and the distance was changed to 50, 100 and 150cm. A human was standing at the center between TX and RX.

Figure 7 shows the measured S21. When the distance between TX and RX was 50cm, a visible difference was observed. The received signal was changed from 90 dB to 75 dB due to the existence of human, which can be used for the human detection. This S21 difference was observed for the distances of 100 and 150cm as well, but the difference became smaller. This is because the attenuation of ultrasonic wave in the air is significant, especially at higher frequency. From this point, lower frequency might be better, but such lower frequency might be detected by human and can be annoying. We here conclude that the horizontal attenuation

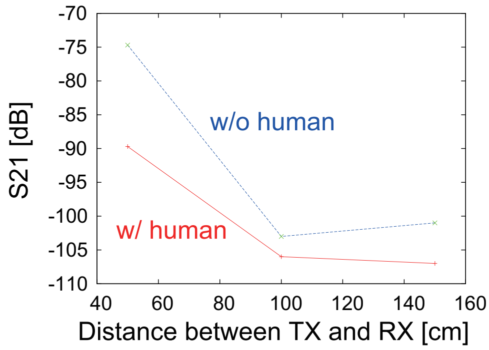


Fig. 7. Experimental result of horizontal attenuation.

can be used for human detection. In the following, we evaluate the feasibility of the invader detection system supposing the sensing method that uses ultrasonic wave attenuation.

IV. Feasibility Evaluation of Invader Detection with Scattered Ultrasonic Sensors

We developed a simulator with C++ language which could evaluate the proportion of invader detection and the system lifetime based on the measured characteristics of ultrasonic sensors. This section experimentally investigates the feasibility of the proposed invader detection system with ultrasonic sensors scattered on the ground.

A. Experimental setup

We assumed that an invader entered the area of interest for the invader detection (10 m × 10 m) randomly in time. The invader first penetrated into the area from the left or bottom boundary and walked diagonally to the top right at the speed of 0.4 m/s. Each invader stayed in the area at least for 2 s. This invader penetration was repeated for many times within 24 hours with an average interval of 2.5 s, which corresponds to a very severe condition from the point of power consumption for wireless communication. We then computed the proportion of the invader detection as the number of invader detections divided by the total number of invader penetrations. The base to which the sensor node needs to wirelessly inform the invader detection was supposed to exist at the coordinate of (15 m, 7.5 m), where the left bottom of the area of interest corresponds to the origin of (0 m, 0m).

As for ultrasonic wave transmission, we have conducted a set of experiments to collect characteristics of ultrasonic communication that depends on the configurations of the locations and directions of transmitter and receiver and the human location. The configuration is shown in Fig. 8, where TX faced to the human. The collected information was used in the simulator to compute the received amplitude by interpolation.

The sensor nodes include two types; ultrasonic transmitter and ultrasonic receiver, and the following explains these.

1) Ultrasonic transmitter: The sensor node of ultrasonic transmitter consists of a timer, ultrasonic sensor for transmission, wireless receiver and battery. This ultrasonic transmitter wakes up based on the timer, and transmits ultrasonic signal

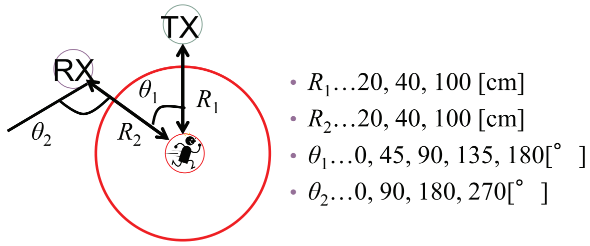


Fig. 8. Setup for collecting ultrasonic communication data.

once a synchronization signal is received wirelessly. Directivity of the transmitter was not considered here assuming a few ultrasonic sensors were driven simultaneously to cover all the directions. This transmitter consumes power when it receives synchronization signal and transmits ultrasonic signal. The power consumption of the timer was ignored.

The energy needed for an ultrasonic signal transmission E_{UT} is given as

$$E_{UT} = C_U V_{CC}^2, \tag{1}$$

where C_U is the capacity of the ultrasonic sensor and V_{CC} is the supply voltage of a CMOS driver. Here, C_U was set to 2550 pF, which was the value of the sensor used for the experiment, and V_{CC} was set to 3.8V, which was equal to the battery voltage supposed in this paper [10].

The energy needed for receiving a synchronization signal E_R was supposed to be [9]

$$E_R = E_{rec} K_R, \tag{2}$$

where E_{rec} is the energy per bit and K_R is the number of bits of the synchronization signal. Here, E_{elec} was set to 50 nJ referring to [11] and K_R was 16.

2) Ultrasonic receiver: The ultrasonic receiver consists of ultrasonic sensor, wireless transmitter and battery. The ultrasonic receiver memorizes the power magnitude of the previously received ultrasonic signal, and when the magnitude changes by over 10 dBm, the ultrasonic receiver sends a signal wirelessly to the base for notifying that an invader is detected. This receiver consumes power when sending the signal of invader detection to the base. In addition, an amplifier and a comparator to receiver ultrasonic signal consume power statically. Here, this comparator was supposed to be used for organizing a successive approximation A/D converter.

The energy for the wireless signal transmission was supposed to be [9]

$$E_T = E_{tra} K_T + \epsilon_{amp} K_T d^2, \tag{3}$$

where E_{tra} is the energy per bit, K_T is the number of bits to send, d is the distance to the base, and ϵ_{amp} is a constant to express distance-dependent energy.

The energy for receiving an ultrasonic signal E_{UR} is

$$E_{UR} = (I_{OP} V_{DD} + I_{CO} V_{DD}) t, \tag{4}$$

where I_{OP} is the current consumption of an operational amplifier and I_{CO} is the current consumption of a comparator.

TABLE I
PARAMETER SETTING.

Parameter	Value
#transmitters	25 (uniformly placed w/ 2.5 m interval)
#receivers	121 / 25 / 9 (uniformly placed w/ 1.0 / 2.0 / 5.0 m interval)
Sensing interval	1.0 s / 3.0 s / 5.0 s / 7.0 s / 10.0 s
Receiver direction	Random in horizontal direction

V_{DD} is the supply voltage of the operational amplifier and comparator, and t is the duration of the circuit operation. Here, we assumed that these two circuits were always active, and hence t was equal to the interval of ultrasonic signal transmission. In this experiment, I_{OP} was set to 1 μA and I_{CO} was 0.3 μA referring to [12] and [13]. V_{DD} was supposed to be the battery voltage, 3.8 V.

B. Feasibility evaluation

We evaluated the proportion of invader detection and the energy consumed in 24 hours. The parameter setting is listed in Table I. We fixed the number of transmitters to 25, and varied the number of receivers and the temporal interval of ultrasonic sensing. Here, the ultrasonic sensor direction was randomly determined for each receiver, and hence 1,000 sets of receiver directions were evaluated in Monte Carlo manner.

Figure 9 shows the average proportion of invader detection as a function of the temporal sensing interval. As the temporal interval of sensing becomes longer, the proportion of invader detection decreases. This is reasonable since an invader can go through the area of interest receiving no ultrasonic sensing as the interval becomes longer. In addition, as the spatial interval of the receiver becomes longer, the proportion of the invader detection degrades. This is due to a fact that the passing route of the invader becomes more possibly distant from the transmitters and/or receivers and the receivers cannot perceive the invader existence. Figure 9 includes a plot labeled upper bound, where the upper bound represents the probability that an invader receives ultrasonic sensing during his/her stay in the area of interest. In other words, the upper bound corresponds to a case that the spatial intervals of transmitter and receivers are very dense, and the proportion of the invader detection is determined by only the temporal sensing interval. As the temporal and spatial intervals increase, the difference between the actual proportion and the upper bound becomes larger. In this test case in which the number of transmitters is 25, the number of receivers should be larger than 121 and the sensing interval should be shorter than 1 s to attain 99% proportion of the invader detection.

Figure 10 shows the energies consumed in 24 hours by a transmitter and a receiver, respectively. The energy of the receiver is independent of the temporal sensing interval, since the power-hungry amplifier and comparator are working for all the time. In our evaluation, the energy consumed by wireless signal transmission was less than 1% of the total energy of the receiver. On the other hand, the energy of the transmitter

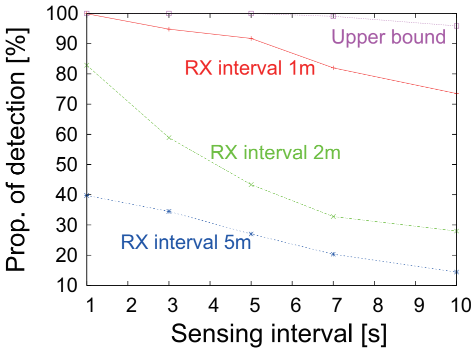


Fig. 9. Proportion of invader detection in case of Table I.

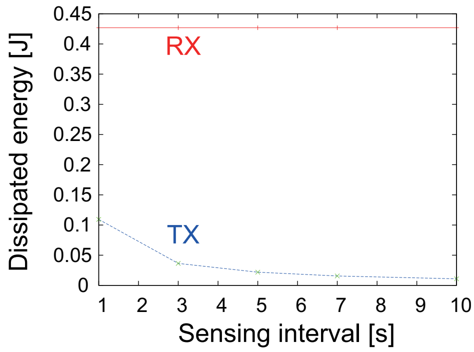


Fig. 10. Dissipated energy in case of Table I.

depended on the temporal interval of the ultrasonic sensing, since the energy consumed by ultrasonic wave transmission was dominant. However, the total amount of the energy of the transmitter was smaller than that of the receiver. Besides, a commercial solid-state rechargeable battery (8 mm $\times$ 8 mm SMT package, [10]) is 0.684 J, and the energies consumed by the transmitter and receiver were smaller than 0.684 J. This means that the transmitter and receiver can be working for years with the rechargeable battery and solar cell. When we use a primary button cell whose capacity can be 684 J, the transmitter and receiver can operate for four years and 17 years, respectively. If we can save the power consumption of the amplifier and comparator, for example, by their intermit operations, we can expect more than 10 year operation without battery maintenance.

C. Impact of random scattering

In the previous subsection, the transmitters and receivers were uniformly placed with a regular interval. On the other hand, when the transmitters and receivers are scattered on the ground, the intervals are not uniform. Supposing the random scattering of sensor nodes, we randomly changed the locations of transmitters and receivers for 100 times and evaluated the average proportion of the invader detection.

We here set the number of transmitters to 284 and 76, and the number of receivers to 441 and 121. We compared the proportions of invader detection between uniform placement

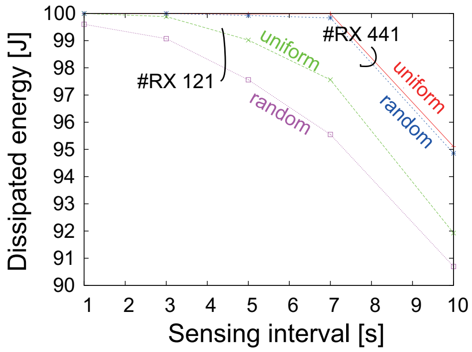


Fig. 11. Impact of sensor scattering on proportion of invader detection (#transmitters 284).

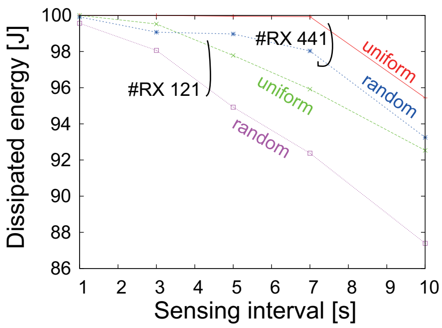


Fig. 12. Impact of sensor scattering on proportion of invader detection (#transmitters 76).

and random placement. Figure 11 shows the proportion of invader detection in the case of 284 transmitters. We can see that the proportion of invader detection degrades when the transmitters and receivers are randomly placed. When the number of receivers was 441, the impact of random placement was very limited, whereas this degradation was visible when the number of receivers was smaller. Giving attention to 99% detection with 121 receivers, the sensing interval of 3 s was necessary for random placement while that of 5 s is enough for the uniform placement. In this case, the degradation due to the random placement can be compensated by increasing the frequency of ultrasonic sensing. Similar tendency was observed in Figure 12 where the number of transmitters was 76. In the case of random placement, the sensing intervals of 1s and 5s were necessary in the cases of 121 and 441 receivers, respectively. The impact of the scatting was not negligible, but could be compensated by adjusting temporal and/or spatial intervals of ultrasonic sensing. The facilitation of the proposed system installation thanks to sensor scatting is promising.

V. Conclusion

This paper proposed an invader detection system that aimed at easy installation and used ultrasonic sensors scattered on the ground, and investigated the feasibility of the system in terms of the proportion of invader detection and energy consumption of sensors. We carried out a number of simulations, which were based on the ultrasonic transmission characteristics obtained by hardware measurement, changing the number of transmitters and receivers and temporal sensing intervals. Experimental results show that, for 10 m $\times$ 10 m area, 99% invader detection was possible with 76 transmitters and 121 receivers. In this case, the ultrasonic sensing was necessary for every second, but even in this case, the transmitters and receivers could be working for more than four years with a primary button cell. Furthermore, the transmitters and receivers could be powered by a small solid-state rechargeable battery and solar cell. Future works includes prototyping of the sensor nodes and performing experiments of invader detection.

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