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Rescue: Wireless power-enabled communication architecture for earthquake rescue operations

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ABSTRACT

In a natural disaster such as an earthquake, it is vital to know the number of people trapped under the ruins. To address this problem, we propose RESCUE – wiREless backScattering CommUnication-based disastEr recovery system. RESCUE is composed of *special* Radio-frequency identification (RFID) readers and sensors that are used to determine the total number of people under the ruins. Passive wireless sensor nodes are placed inside the building during construction and are equipped with a camera that is activated during an earthquake. After the earthquake, communication to the passive tags of sensors is achieved by wireless power transfer from a reader located outside the ruins. Tags harvest this energy and send the image data stored by the camera. We also design an antenna structure to maximize simultaneous wireless information and power transfer (SWIPT) for devices under ruins. We analyze the communication channel between reader and sensors and derive a channel model over ruins. Furthermore, we obtain the results of experimental study where we validate the derived channel model. Results show that RESCUE can collect the desired data in a relatively short time, and hence, is a promising disaster recovery system architecture.

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1. Introduction

During search and rescue operations after an earthquake, it is of utmost importance to locate the people under ruins in the shortest time. Generally, search and rescue of people trapped under rubble involves the use of sound detecting devices, victim location identification with trained dogs, visual spot examination [1] and witness questioning [2]. However, these techniques are inadequate in obtaining conclusive information about trapped victims. New reliable and robust systems are needed.

Two main problems that need to be addressed during victim rescue operations are identifying total number of people trapped under the rubble and their locations. Once this information is available, rescue teams can be allocated more efficiently to rescue victims from the under building ruins in the shortest possible time.

In this study, we present RESCUE, which, to the best of our knowledge, is the first wireless power-enabled, backscattering communication-based disaster recovery system that is able to provide vital information, e.g., the number of people trapped under ruins and their probable locations, which can be used during

search and rescue operations. RESCUE consists of a *special* RFID reader and passive sensors, equipped with passive RFID tags. We develop a model, where we take into account path loss, multipath fading and shadowing that occur during communication through rubble. To describe power loss over building ruins, we use an earthquake simulator software [3]. After constructing a building, earthquakes with various parameters can be applied to the building with the simulator to obtain different collapse structures. Using these collapses, we evaluate the power loss between reader outside the ruins and the sensors at different locations inside the ruins.

To validate the possibility of reading a passive sensor under ruins, we have also carried out an experimental study. We placed a standard UHF RFID reader and an RFID tag in an environment, where they are separated by a medium made of reinforced concrete, brick and other construction materials. By using a directional antenna on reader, we were able to read data on a tag. Using spectrum analyzer, we have measured received power level near the tag to experimentally calculate the channel power loss. Our measurements confirmed the results predicted by the theoretical channel model.

The rest of the paper is organized as follows. In Section 2, we present the related work. In Section 3, RESCUE system model is given, where we discuss the details of our proposed approach.

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The channel model is introduced in Section 4, where power loss model and transmission power are given. In Section 5 we present the simulation details, simulation results and the details of our experimental study. Finally, conclusions are given in Section 6.

2. Related work

Communication system design for disaster recovery and management is currently a hot research topic [4,5]. Use of RFID tags during disaster relief situations have been proposed in a number of studies. Resource management during rescue operations and possible advantages of using RFID tags have been discussed in [6]. In [7], authors discuss attaching RFID tags to people rescued from ruins for ease of tracking their medical condition. Placing RFID tags on collapsed building and forming an Ad-Hoc network of mobile devices with RFID readers for distribution of structural integrity is presented in [8]. However, none of these methods are about rescuing victims. Moreover, the performance analysis of these schemes have not been done.

The idea of utilizing RFID tags for finding victims under the ruins has been proposed in [9]. Since communication through a channel full of rubble creates many multipath components, finding the location of a tag can be difficult. However, the authors do not examine this problem in the paper. In [10], it is suggested that people could wear passive tag equipped objects such as rings or wristbands and these objects can be detected with an RFID reader to calculate total number of victims under rubble. Exploiting passive RFID tag for finding number of victims have been put forward in [11]. Authors discuss attaching RFID tags inside apartments with resident information in these tags. However, in both studies, authors neither investigate passive communication challenges nor do they give any technical results.

In [12], authors describe the total power loss through a channel with ruins equal to the sum of free space path loss and attenuation through medium with construction materials such as concrete, brick, cement. The distribution of these materials in a channel is assumed to be Gaussian. However, no measurement is taken to confirm the assumptions used in deriving the model. Also, the channel model presented does not take into account the losses due to effects of multipath. In contrast, authors consider the effects of multipath fading for channel model in addition to losses due to obstacles in [13]. However, the channel model is based on indoor signal attenuation model given in [14], and therefore, only considers walls as obstacles. As walls are often built using mostly bricks, the model does not fully characterize the total power loss through channel with ruins, which also include concrete, wood, glass, etc.

Although various approaches have been previously introduced, to the best of our knowledge, RESCUE is the first study to propose a disaster recovery system based on simultaneous wireless information and power transfer (SWIPT), with a complete and fitting channel model, validated with experimental results.

3. System model

In this section, we present an overview of our system model and explain our extensions to RFID simulator.

3.1. Overview

RESCUE system model is illustrated in Fig. 1. It consists of sensors (i.e., red dots) located inside the building and a reader. After an earthquake, sensors remain under the rubble and a reader is used from outside the ruins to read the data stored by the sensors.

Each RESCUE sensor consists of six modules, i.e., camera, earthquake detector, microcontroller, passive RFID tag, power

Fig. 1. System architecture. The reader reads data from sensors under ruins.

Fig. 2. RESCUE dodecahedron antenna structure.

Table 1

Example models of the RESCUE sensor components.

Component	Model
Microcontroller	MSP430F5328 – EP
Earthquake detector	Model 832 Accelerometer
Camera	TCM8230MD
Passive RFID Tag	TegoChip
Ultracapacitors	VEC5R0755QG, VEC3R0507QA
AC – to – DC regulator	MAX610
Antenna switch	6 × ADG787

Table 2

Power requirements of sensor components.

Component	Power requirement	Minimum supply voltage
Microcontroller	7 mW	1.8 V
Earthquake detector	13.2 μ W	3.3 V
Camera	53 mW	2.6 V
Antenna switch	0.6 μ W	1.8 V

source and antenna switch. The task of a sensor is to detect the occurrence of an earthquake, take images of the room in that instant and store that information. When first responder units arrive, they use a reader to retrieve the image data stored in the RESCUE sensors and determine the locations of people under the rubble by matching the ID of the sensor with their corresponding locations. The model of each component that can be used in the RESCUE sensor is given in Table 1. Two ultracapacitors power separate parts of a sensor. These are used as alternative power sources since building electrical power is often cut off at the time of an earthquake. These ultracapacitors are only used during the earthquake, to activate the system, take photos and provide power to the microprocessor to store the data to RFID tags.

Minimum operating voltage for earthquake detector, camera, microcontroller and antenna switch are given in Table 2. Earthquake detector is connected to VEC5R0755QG ultracapacitor, which can provides 5 V (3.3 V through a voltage regulator [15]) and has 7.5 F capacitance and the other components power up from VEC3R0507QA, ultracapacitor with 3 V rated voltage and 500 F capacitance.

At the time of an earthquake, the earthquake detector triggers microcontroller, which activates the camera through serial I²C interface [16]. The average duration of an earthquake is about 50 s [17]. To be safe, we propose that the sensors take pictures for hundred seconds. In total, ten images are taken during this period. The images are encoded in JPEG format with 8 kB image

Fig. 3. Radiation pattern of two faces of a sensor for horizontal and vertical polarization, respectively.

size [18] and saved into RFID tag memory, also via I^2C interface between microcontroller and passive RFID tag.

To maximize read range of sensors, the reader should use a directional antenna. However, at the time of collapse, a sensor can end up at any arbitrary orientation. To guarantee reliable data reading, sensors should be accessible to a reader from any direction. We propose using an antenna shell around sensors in the shape of polyhedron with a directional antenna attached to each face as shown in Fig. 2. The sensor is capable of using the antenna directed to the reader. Sensor detects the antenna with highest level of incident RF and uses that antenna during transmission and reception to maximize sensor effective isotropic radiated power (EIRP). In Fig. 3, we show radiation pattern of two adjacent directional antennas of a sensor for horizontal and vertical polarization. Radiation pattern data belongs to Omni-Id Dura 3000 [19] tag antenna. It can be observed that the reader signal coming in the direction of one of the antennas will be largely attenuated on adjacent directional antennas. Even though there are many multipath components coming from the rubble, since one of the antennas receives the line-of-sight (LOS) component of the reader signal, the total receive power level at that antenna will be larger than other antennas. The microcontroller compares the moving average value of power on each antenna and chooses the antenna with highest moving average receive power for the communication. MSP430F5328 – EP has total information memory of 10 kB. Each sample of the A/D converter of the microcontroller is 12 bits. Therefore, for a dodecahedron (12 faces) shaped sensor, moving average of 20 samples can be used for antenna selection. Antenna input is connected to the antenna with the highest incident RF power.

Total available energy inside the ultracapacitor can be calculated as

$$E = \frac{1}{2} C (V_{initial} - V_{min})^2 \quad (1)$$

where C is capacitance, $V_{initial}$ is the initial voltage of the ultracapacitor and V_{min} is the minimum operating voltage of the component being fed. According to Table 2, VEC5R0755QG can feed earthquake detector for 9.5 days without external power. Before an earthquake, microcontroller is in the standby mode. Earthquake detector activates the microcontroller at the time of an earthquake. Microcontroller stays in the active mode until ultracapacitor energy can no longer provide the required operating voltage. Taking into account voltage requirements of microcontroller, camera and antenna switch along with power requirements in Table 2, it can be calculated using (1) that the sensor can stay functional for approximately 14 h. As it can be seen in the performance evaluation in Section 5.1, this period is sufficient for successful data collection from sensors.

3.2. Extended RFIDSIm simulator

RFIDSIm [20] is a software that can simulate communication between an RFID reader and passive tags. The reader element

inside RFIDSIm lacks some of the features of an actual passive RFID reader. We extended the simulator to include two more capabilities to the reader module. The first addition is the ability to read data from tag in more than one round. Once a tag enters *Open* or *Secured* state, the reader should be able to send any number of access commands according to C1Gen2 protocol. However, the simulator only lets a reader send one access command for each run. It is faster for a reader to be able to access the data on the tag piece by piece by sending a number of *Read* commands. This is because as the bit error rate (BER) of a channel increases, the reader needs to request smaller amount of data from the tag in each *Read* command. Secondly, the data sent from the tag to the reader includes a 16-bit checksum. When the checksum of a received data from a tag is incorrect, the reader should be able to request the same data again. We have added this feature, which is not included in RFIDSIm.

4. Channel model for passive wireless communication over ruins

In this section, we detail our channel model. First, we state power loss expression and derive the bit error probability of the channel. Next, we describe the building collapse simulator, and explain how it is used to calculate power loss between the reader and the sensors. Finally, required reader transmission power is discussed and equations are given.

4.1. Power loss

Power loss is mainly due to path loss and shadow fading. Hence, using a modified form of simplified path loss model, the power loss is

$$PL(dBm) = -20 \log\left(\frac{c}{4\pi f d_0}\right) + 10\gamma \log\left(\frac{d}{d_0}\right) + L_{SHDW} \quad (2)$$

where f is the signal frequency, c is the speed of light, d_0 is reference distance, d is the distance between reader and sensor, γ is path loss exponent, and L_{SHDW} is the power loss due to shadowing. Since shadowing represents a portion of a signal that does not pass through a certain medium, it can be represented by the transmission coefficient of a medium that signal is passing through. Given that there exist n obstacles between reader and sensors, shadow loss can be calculated as

$$L_{SHDW} = \sum_{a=1}^n -20 \log T_a \quad (3)$$

where T_a is a transmission coefficient of a th obstacle between the reader and the sensor, and for a material with permittivity ϵ and conductivity σ it can be modeled as a three layer medium (air-material-air) [21]

$$T_a = \frac{4}{(1 - Z_{12})(1 - Z_{23})e^{-\gamma_2 d} + (1 + Z_{12})(1 + Z_{23})e^{\gamma_2 d}} \quad (4)$$

Fig. 4. Simulated six different collapse scenarios.

$$Z_{ij} = \frac{\mu_i \gamma_j}{\mu_j \gamma_i} \quad i, j = 1, 2, 3 \quad (5)$$

$$\gamma_k = \pm \sqrt{j\omega \mu_k (\sigma_k + j\omega \epsilon_k)}$$

where d is depth of the medium, μ is magnetic permeability, ω is angular velocity, and γ is the complex propagation constant. Electrical properties of materials are taken as ($\epsilon_{concrete} = 5.31$, $\sigma_{concrete} = 0.033$ S/m), ($\epsilon_{brick} = 3.75$, $\sigma_{brick} = 0.038$ S/m), ($\epsilon_{wood} = 1.99$, $\sigma_{wood} = 0.005$ S/m) [22].

By using (3), (4) and (5), we depict the shadowing of construction materials. Calculated attenuation values are in agreement with the results reported in other studies [23]. Since shadowing through wood is considerably less, we eliminated wood from our calculations for this study.

4.2. Bit error probability of the channel

To the best of our knowledge, there is no closed form expression for BER in a Rician fading RFID communication channel. Average BER for a rician fading channel can be calculated using [24]

$$P_e = \int_0^\infty P_b(\gamma) f_\gamma(\gamma) d\gamma \quad (6)$$

where $P_b(\gamma)$ is probability of error in an additive white Gaussian noise (AWGN) channel and f_γ is the probability distribution function (PDF) for Rician distribution. BER in an AWGN channel for RFID communication can be obtained from [25]

$$P_b = 2Q(\sqrt{M\gamma})[1 - Q(\sqrt{M\gamma})] \quad (7)$$

where $Q(x)$ is the Q-function and M is number of cycles in tag's data encoding scheme. Rician fading probability distribution is given as [26]

$$f_\gamma(\gamma) = \frac{K+1}{\bar{\gamma}} \exp\left[-K - \frac{\gamma(K+1)}{\bar{\gamma}}\right] I_0\left[2\sqrt{\frac{\gamma K(K+1)}{\bar{\gamma}}}\right] \quad (8)$$

where $\bar{\gamma}$ is average effective signal to noise ratio (SNR), K is the ratio between dominant signal component and other multipath components, and $I_0(x)$ is the zero-order Bessel function of the first kind.

We solved the integral in (6) by employing Gaussian-Legendre quadrature [27] numerical integration method. The integral can be expressed as

$$P_e = \int_0^{\gamma'} P_b(\gamma) f_\gamma(\gamma) d\gamma \quad (9)$$

where γ' is a large number. By rearranging (9), using $\gamma = a \cdot x + c$ and taking the range of x as $[-1, 1]$, such that $a = \frac{\gamma'}{2}$ and $c = \frac{\gamma'}{2}$,

$$P_e = \frac{\gamma'}{2} \int_{-1}^1 P_b\left(\frac{\gamma'}{2}x + \frac{\gamma'}{2}\right) f_\gamma\left(\frac{\gamma'}{2}x + \frac{\gamma'}{2}\right) dx$$

$$\approx \frac{\gamma'}{2} \sum_{i=1}^n w_i P_b\left(\frac{\gamma'}{2}x_i + \frac{\gamma'}{2}\right) f_\gamma\left(\frac{\gamma'}{2}x_i + \frac{\gamma'}{2}\right) \quad (10)$$

$$w_i = \frac{2}{(1-x_i^2)(P_n(x_i))^2} \quad (11)$$

using Gaussian quadrature method, where n is the number of points used for numerical calculation. We used $n = 10$. The weight coefficient of the i th point is denoted as w_i and $P_n(x)$ is a Legendre polynomial, which can be expressed using Rodrigues' formula [28] as

$$P_n(x) = \frac{1}{2^n n!} \frac{d^n}{dx^n} [(x^2 - 1)^n] \quad (12)$$

Using (10), we evaluate BER in the channel between the RESCUE reader and sensors. BER is then used to obtain total read time of data inside RESCUE sensors.

4.3. Building collapse model

The building collapse model is based on ASI-Gauss [3] technique. Isobe Lab research group at University of Tsukuba has developed this technique and has also released a seismic collapse analysis simulator that can be used to construct structures and apply the proposed technique. We have used this simulator for our study.

The structure we have built for this study has five floors, with two apartments on each floor. Each apartment is made of four rooms. The overall dimensions of the deployed structure model are (8 m) $\times$ (16 m) $\times$ (12 m). We have carried out seismic collapse analyses on the structure by varying parameters and obtained six different collapses that might occur as a result of a destructive earthquake. Fig. 4 illustrates these scenarios, which are used for performance evaluation of RESCUE.

Fig. 5 depicts placement of sensors in an apartment of a building. There is one sensor per room and they are shown in black dots. It is assumed that the sensors will remain attached to the corners of rooms after building collapse.

4.4. Communication medium model

Since shadow fading plays a significant role in determining overall power loss of the channel, it is imperative to describe the channel in terms of materials present along the communication link. Concrete slabs and brick walls inside the rubble are considered as individual cuboids. We propose a technique to determine if a point in three dimensional space is inside a given cuboid so that we can deduce the amount of concrete and/or brick walls in the communication channel between the sensor and the reader.

Fig. 5. An apartment in a building. Sensor locations are shown in black dots.

Fig. 6. A cuboid and an arbitrary point P in 3D space.

In Fig. 6, a cuboid is shown. $ABCD$ is a rectangle that lies on a plane, parallel to and located in the middle of upper and lower surfaces of the cuboid. It is possible to analytically determine whether a given point $P(x, y, z)$ is inside the cuboid. To achieve this, two conditions need to be satisfied. First, distance from the point to the plane that $ABCD$ is located on should be calculated. If the distance is lower than half of the height of the cuboid h , then the second condition should be checked. For the second condition, θ angles need to be evaluated using

$$\theta_A = \arccos\left(\frac{(\vec{AB} \times \vec{AP}) \cdot \vec{n}}{|\vec{AB} \times \vec{AP}|}\right) \quad (13)$$

$$\theta_B = \arccos\left(\frac{(\vec{BC} \times \vec{BP}) \cdot \vec{n}}{|\vec{BC} \times \vec{BP}|}\right) \quad (14)$$

$$\theta_C = \arccos\left(\frac{(\vec{CD} \times \vec{CP}) \cdot \vec{n}}{|\vec{CD} \times \vec{CP}|}\right) \quad (15)$$

$$\theta_D = \arccos\left(\frac{(\vec{DA} \times \vec{DP}) \cdot \vec{n}}{|\vec{DA} \times \vec{DP}|}\right) \quad (16)$$

where $\vec{n}$ is the normal vector of the plane that $ABCD$ lies on. If all four θ values are smaller than $\pi/2$ or bigger than $\pi/2$ at the same time, then, the point is inside the cuboid. Otherwise, the point is located outside the cuboid.

4.5. Reader transmission power

One of the main aims of this study is to determine appropriate transmission power for the reader. To successfully read data from a passive sensor, two conditions need to be satisfied. Firstly, the received, i.e. harvested power, of the sensor should be higher than its RFID tag activation power. Secondly, power reflected from the sensor has to be higher than the reader's sensitivity level. By combining these two conditions, the required minimum reader transmission power to read data from a sensor is expressed as

$$P_{TXmin}(dBm) = \max\left[\left(P_{RS} + 2PL - 2(G_R + G_T) - 20\log(\rho)\right), \left(P_{ac} + PL - (G_R + G_T)\right)\right] \quad (17)$$

Fig. 7. Distribution of minimum power loss values for 6 different collapse scenarios.

where P_{RS} is reader sensitivity, PL is power loss between reader and sensor, G_R and G_T are antenna gains of reader and sensor respectively, ρ and P_{ac} are sensor RFID tag backscatter power ratio and activation power respectively. Reader received signal SNR can be evaluated as [29]

$$SNR = P_{RDrec} - NF(dB) - 10\log(BW) - (-174) \quad (18)$$

where P_{RDrec} is the reader received signal power, NF is the noise factor, BW is the total bandwidth of the receiver and -174 is the effective noise power available in 1 Hz bandwidth at 290 K temperature. P_{RDrec} can be expressed by

$$P_{RDrec} = P_{TXmin} - 2PL + 2(G_R + G_T) + 20\log(\rho) \quad (19)$$

5. Results

In this section, we first explain our simulation environment and present the simulation results. Then, we detail our experimental study and its results which consists of received power measurements from an RFID tag under the rubble.

5.1. Simulation environment

In the simulations, we aim to determine total read duration and transmission power for optimal performance.

5.1.1. Power loss

A simulation is carried out to derive channel content for every sensor from each reader location. Using channel content, total power loss is calculated by (2). Finally, minimum of calculated values for each sensor is selected as power loss between reader and sensor, because we can just place the reader to that minimum loss position and start data collection.

For determination of the content of the debris along the channel, concrete width and brick wall width are 30 cm, and 5 cm, respectively. The number of discrete points on the link between reader and sensor is 10^5 . Rest of the parameters are as follows: $f = 866$ MHz, which is the frequency at which the experimental study was conducted, $d_0 = 0.5$ m, $\gamma = 4$, which were chosen based on channel density.

There are 4 sensors in each apartment and 10 apartments in the 5 floor building. The distribution of the lowest power loss values is given in Fig. 7. The figure represents power loss values from all 6 collapse scenarios. As a result, a total of 240 power loss values are represented in the graph. The lowest value for power loss is around 45 dB and highest value is close to 90 dB. The highest distribution of values is between 65 dB and 85 dB.

Fig. 8. Bit-error-rate for different tag data encoding schemes in RFID Rician fading channel.

Fig. 9. Total read time of images from 40 sensors under ruins vs. transmission power.

Table 3
RFIDSim simulation parameters.

Parameter	Value
Reader Tari value	25 μ s ($\approx$ 32 kbps)
MAC layer delays	None
Tag backscatter ratio	15%
Reader antenna gain	13 dB
Tag antenna gain	10 dB
Operation frequency	866 MHz
Background noise	-100 dBm
Noise factor	22 dB
Receiver bandwidth	1.6 MHz
Temperature	290 K ($\approx$ 16.85 $^{\circ}$ C)
Reader sensitivity	-90 dBm
Tag sensitivity	-18 dBm

5.1.2. Read time and transmission power

Parameters used during simulation are given in Table 3. Type-A reference interval (Tari) defines the duration of Zero symbol, and can range from 6.25 to 25 μ s. In the experiment, we used Omni-ID Dura 3000 tag with activation power of -20 dBm. Free space read range of this tag is 35 m with 30 dBm transmit power. Using this information, tag antenna gain can be calculated as 12 dB. Since power coming from the antennas also passes from the envelope detector of a sensor, some of the energy is dissipated on the envelope detector resistors. Therefore, we take sensor antenna gains to be 10 dB. Since tag activation power is much higher than noise, and data length sent by the reader is short, we neglect bit-errors on tag's side. Reader sensitivity is taken as -80 dBm [30].

BER is evaluated using (10). γ' is taken as 10^5 and Rician fading parameter is taken as $K = 10$. The resulting BER values are shown in Fig. 8. Each curve corresponds to a different cycle number (M), for a different encoding scheme.

The total time spent by reader transmitting power to read one image from all 40 tags is evaluated using RFIDSim simulation and is shown in Fig. 9. It can be observed that for high transmit power, read time decreases to approximately 200 s. Also, note that the total read time is directly proportional to the amount of data

Fig. 10. Read time of one image from every sensor during partial reading of sensors under ruins for all six cases.

Fig. 11. Read time for different word sizes and tag data encoding schemes.

Fig. 12. The distribution of fraction of concrete in the channel between reader and sensors under ruins.

reader requests from sensors. As a result, if reader chooses to read higher number of images, read time increases accordingly.

One of the parameters of a *Read* command is the word size of the data requested from a sensor. Depending on receiver *BER*, read time of a sensor may dramatically change. Another parameter that affects read time is tag data encoding cycle number. In Fig. 8, we show how *BER* changes with *SNR* for 4 different encoding schemes. The number of cycles increases as the tag data encoding scheme is changed from *FM0* to *Miller – 8*, and the duration of each bit during backscattering doubles. Longer bit duration results in fewer bit-errors. Therefore, there exists a trade-off between decreasing total read time and minimizing *BER*. Fig. 11 shows read time of one sensor for 4 different *M* and *BER* values. When calculating total read time shown Fig. 9, we pick the most optimal word size and cycle number for every request, depending on reader *SNR*. Even though *M* is specified during *Query* command, in order to set optimal *M*, reader can send a second *Query* command by taking into account the *SNR* of the first sensor response signal.

For the data shown in Fig. 9, time axis represents the total time spent by reader to read all data on all sensors. With lower power levels, sensors under ruins can be partially read. The total time spent and transmitted power level to read data from only certain percentage of tags are given in Fig. 10. As reader transmission power increases, the number of sensors that can be read increases as well. In the figure, the reading of a new sensor results in an increase in read time. As the transmission power increases

Fig. 13. The distribution of fraction of brick in the channel between reader and sensors under ruins.

Fig. 14. Reader transmission power with read time of one image from one sensor for buildings of 2–20 floors.

further, the total read time starts to decrease until another sensor is read. This is, similarly, due to the fact that *SNR* increases with the transmission power, which decreases total read time.

Fig. 9 represents the read time and transmission power for collapsed 5 floor building. To determine the required transmission power for various floor buildings, we use simulation data from simulated 5 floor building collapse. One of the main components of power loss in the channel is shadowing. Figs. 12 and 13 show the fraction of concrete and brick in the channel for the simulated 5 floor building collapses. We use concrete and brick fractions corresponding to 0.9 The cumulative distribution function (CDF) to evaluate maximum transmission power that is needed to read all the sensors under ruins. Fig. 14 illustrates calculated transmission power levels and read times to access one image from one sensor for building sizes ranging from 2 to 20 floors.

Fig. 15 shows average data rate in tag-reader communication with increasing *SNR*. Data rate starts to saturate around 135 kbps at 30 dB *SNR*, similarly due to decrease in *BER*.

Even though reader transmission power levels shown in Fig. 14 are much higher (10 W – 1 MW) than allowed by regulations in UHF band, i.e., 2 W EIRP in Europe and 4 W EIRP in US, proposed reader is to be used only for emergency disaster recovery operations and only for a short period of time to save lives.

Fig. 15. Average data rate during backscattering for different SNR values.

Fig. 16. Experimental equipment diagram.

5.2. Experimental study

In this section, we first describe all hardware and software tools that have been used to realize the experiment. Then, we specify the details of experimental setup, and how the experiment have been carried out. Finally, we present the results.

There are two main goals in the experimental study. The first goal is to read data on a passive RFID tag, when the reader and tag are separated by a medium consisting of brick and concrete materials. The second goal, is to measure the receive signal power strength at the location of the tag, where it is being successfully read by the reader. By using received power magnitude, we calculate the power loss between reader and tag. We compare the values from the experiment by the theoretical results obtained by the channel power loss model given Section 4.

5.2.1. Experimental setup

Impinj R420 RFID Reader was used for the experimental study. The antenna that was employed in the experiment is MT-243017/

NRH. The antenna is circularly polarized and has gain of 11 dBi, which is approximately equivalent to 9 dBi. Passive RFID Tag used in the experiment is Omni-ID Dura 3000. The tag has 35 m read range with 30 dBm transmit power in free space. The user memory of the tag is 512 bits. To operate the reader, Impinj MultiReader Software was used. By connecting the Impinj RFID Reader, the software can send any C1Gen2 protocol command to tags. For spectrum analysis, we use Universal Software Radio Peripheral (USRP) and GnuRadio software. USRP is a software-defined radio that connects to a computer and serves as a wireless communication front-end. GnuRadio is a software toolkit to be usually used with an RF front-end hardware such as USRP. We used a software built on GnuRadio to display power magnitude of the signal present on USRP antenna.

The equipment diagram is shown in Fig. 16. The USRP is connected to a computer as mentioned earlier. The computer is connected through WiFi to the Router, that is also linked up with the RFID Reader. This provides an easy way to wirelessly control the reader from a computer.

5.2.2. Experimental results

We carry out experiments and take measurements for three different media between tag and reader. In the first two cases, we take measurements and read the tag through brick wall and concrete slab mediums between the reader and the tag, respectively. The transmission power of the reader is set to 30 dBm and hence with the effect of antenna gain, total EIRP is 39 dBm.

In the first case, the medium is a 50 cm wide brick wall. Reader antenna and USRP are placed on opposite sides of the wall to measure signal attenuation. The distance between two devices is around 80 cm. Spectrum measurement obtained through USRP is given in Fig. 17(a). Received power, as it can be seen from the graph, is roughly 15 dBm, which corresponds to 24 dB power loss. This value is compared to theoretical calculation using (2), which is equal to 26.6 dB.

In the second case, measurements were taken for reinforced concrete medium. As a medium we use reinforced concrete floor separating two floors of a Koç University building. The width of the reinforced concrete is 40 cm. Reader and antenna were placed on upper floor, with antenna facing down while tag and USRP were on the lower floor, with tag facing up. The measurement of received power is shown in Fig. 17(b). With 1.6 m separation between antenna and USRP, receive power is -10 dBm. Thus, measured power loss between antenna and tag is 49 dB. Using power loss expression (2), the theoretical value of total power loss is 45.6 dBm.

The third case was realized with a real rubble in an environment with ruins. Images of setup are given in Fig. 18. Fig. 18(a) shows the placement of antenna and tag with respect to rubble. Antenna is placed on top of the rubble, as shown in Fig. 18(b) and tag, along with laptop and USRP, is put under the rubble as shown in Fig. 18(c). Fig. 18(d) shows other hardware.

Fig. 17. Measurements of received power with mediums (a) brick and (b) concrete (c) ruins with a combination of materials.

Fig. 18. Images of experiment setup in the area with ruins.

Closer image of the medium between antenna and tag is given in Fig. 18(e). As it can be seen, the medium is made of both reinforced concrete and brick. Approximate width of concrete section is 40 cm and width of brick section is 10 cm. During measurements, we fix the tag higher from the ground. The total distance between antenna and tag is around 1.5 m at the time of measurements and reading. Fig. 17(c) shows received power at the point of tag location. Measured power level by USRP is -15 dBm, and therefore, power loss through the rubble can be characterized as 54 dBm. The equivalent theoretical value for power loss is 51.5 dBm, which is very close to experimentally measured power loss.

Slight discrepancies between the values in all cases are expected. Furthermore, it should also be noted that in the third case of the experiment, tag was only readable when directional antennas of tag and reader were face to face. This confirms that the fading on the channel is Rician.

6. Conclusions

In this study, we evaluate the performance of passive communication through channel with collapsed building ruins. We propose RESCUE system that consists of a special RFID reader and sensors. Sensors store pictures of building interior taken at the time of an earthquake using sensor cameras. After an earthquake, a reader collects image data from sensors to estimate total number of victims trapped under ruins. A power loss model that takes multipath fading and shadowing effects into account is developed. Moreover, we use an earthquake simulator to obtain different building ruins and these ruins are used in the theoretic study to evaluate the performance of RESCUE. Total read time of all the sensors and corresponding transmission power values are calculated for various floor buildings. Finally, we present the results of an experimental study. We successfully read a passive RFID tag in three different medium types. We plot measured receive power levels and calculate the experimental power loss for all three cases, proving that our channel model is accurate.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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