Characterization of the Electromagnetic Propagation through Building Rubble by Means of Numerical Random Models

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Abstract— In this work we propose random models representing collapsed building rubble to evaluate phenomena of attenuation and propagation of radio signal through this kind of transmission medium. The aim of the work is to offer a valid propagation channel model to facilitate, in case of emergency, rescue operations using modern technologies employing RF signals. The models involves different materials and the propagation is examined for several conditions of the rubble (degree of compression, graininess etc.). The study permits to estimate the Path Loss by calculating mean, standard deviation and minimum value for a large number of scenarios to provide a statistical analysis of the collected data.

1. INTRODUCTION

The rescue of victims buried in building rubble because of earthquakes, landslides, explosions in industrial plants or terrorist attacks, can take advantage from real-time measurements employing wireless communications devices.

Rising technologies like rescue robots, allow rubble exploration and victims localization exploiting radio signal transmissions [1, 2]. Moreover, radio detection of vital signs or detection of radio signals emitted by personal RF devices (e.g., cell-phone, radios, RFID, etc.) that may be close to the owner (especially in case of rescuers involved in subsequent collapses) can be very useful in post emergency operations since immediacy of action may lead to a considerable reduction in the number of victims [4–8]. For these reasons communications plays a big role in this kind of systems. These operations efficacy however, is strictly related to the characteristics of propagation channel in the disaster scenario. Attenuation, multipath and noise make the radio-link weak and untrustworthy, in spite of this adequate systems can be designed if a sufficiently accurate knowledge of the features of the propagation channel is available.

This work has been developed after the earthquakes which stroked the Italian territory in the last years. The considered scenarios are then composed by rubble and debris of collapsed buildings, that is a very complex environment because of different materials, morphologies of urban fabric involved and physical characteristics of rubble and debris (i.e., shape, dimensions, humidity and level of compression), for which no general channel model exists [9–11]. The characterization of electromagnetic propagation in complex medium consisting of different materials arranged in random and variable manner as building rubble is very difficult and there are few studies on this topic in the literature. Some models are based on artificial scenarios while other are specialized to specific models as the layered model of rubble [10] which unfortunately seems too ordered and simplified when compared to real cases.

In this work, in a completely new way compared to the literature, we simulate different models of rubble to evaluate phenomena of attenuation and propagation of radio signal through an extremely heterogeneous transmission medium structured in a not predictable manner.

The aim of the work is the development of a random model of the rubble that would reflect a wide range of environments, for this reason random rubble scenarios were generated and simulated through an electromagnetic tool where the transmission source is represented by a dipole antenna buried into rubble. The model involves typical materials, in established and plausible proportions, of both modern buildings (concrete, bricks and iron) and ancient ones (stones and bricks). A number of parameters characterize the model of the rubble: the degree of compression (defined as the ratio between the empty and filled spaces), the graininess (i.e., the size of the blocks of homogeneous material), the number of different materials, the dielectric properties of each material, the moisture, the thickness of the layers (one or more layers are considered). A large number of simulations have been performed for different frequencies: at 13 MHz, 432 MHz and 900 MHz. These frequencies have been chosen because they mainly concern rescue devices and are near the frequency bands of many communication services in Italy and European Countries. The study is focused on the analysis of Path Loss at different heights from the ground and for various angles of incidence of the electromagnetic wave. A statistical analysis of data are also carried out by calculating mean, standard deviation and minimum value of Path Loss for a large number of simulations.

The proposed model takes cue from a measurement campaign carried out in a number of buildings collapsed or partially destroyed in L'Aquila territory that was stroked by a severe earthquake in 2009 [12, 13].

Comparison between model results and measurement data allow us the tuning of the model parameters and is under development.

In the following sections the developed models and the simulation results are shown.

2. PROPOSED MODEL

We propose a realistic numerical model made up of cubes of various materials and sizes arranged in a random way to represent the scenario of a collapsed building with good approximation. It plies blocks of different materials to form a heap having the shape of a big prism with square basis. Each block has the dielectric properties of a material randomly selected from a predefined list. Also blocks of air are included in the model to take into account the void spaces present in a real heap of rubble. The heap of rubble is resting on a layer of moist soil having dielectric characteristics to absorb the electromagnetic radiation completely, so that it permits to simulate the behavior of the real soil conditions with a layer of reduced thickness. A transmitter is placed in the heap of rubble at a point near to the soil. It is modeled as an ideal voltage generator connected to the terminals of a dipole antenna. The propagation through the rubble and out of the heap of rubble is studied by means of a full-wave analysis based on FDTD (or similar Time-Domain approaches, e.g., FIT — Finite Integration Technique) method. Because FDTD is computational cumbersome the geometrical size of the model is limited to $5\,\mathrm{m} \times 5\,\mathrm{m}$ corresponding to a medium/large room in order to have a manageable computational charge. Numerical analysis has been performed on a personal computer having 48 GB RAM and twelve 2Core Intel processors.

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2.1. Materials

Modern buildings made of concrete and ancient ones in stone and sand are considered. In Table 1 the list of used materials and the corresponding dielectric parameters are reported [14–18], iron is also included but it is modeled as PEC material. For the ground a relative dielectric constant of $\varepsilon_r = 10$ and a conductivity of $\sigma = 0.1\,\mathrm{S/m}$ are assumed [13].

These parameters are constant for all simulation frequencies.

Table 1: List of materials.

Material	ε_r	σ **[S/m]**
Concrete	6	0.005
brick	4.45	0.031
stone	4	0.02
sand	3	0.01

2.2. Degree of Compression

A significant parameter, typical of each real condition, is the level of compression of the rubble. Here, it is defined as the ratio between full and empty space for the scenarios.

Naming V_{solid} the volume occupied by walls and ceiling (i.e., $V_{\text{solid}} = V_{\text{walls}} + V_{\text{ceiling}}$), V_{air} the volume of the empty spaces inside rubble and V_{tot} the total volume occupied after the collapse, the degree of compression is

$$\mathrm{DoC}(\%) = \frac{V_{\text{solid}}}{V_{\text{air}}} \cdot 100 = \frac{V_{\text{walls}} + V_{\text{lofts}}}{V_{\text{tot}}} \cdot 100 \tag{1}$$

As an example, assuming that a room of $25\,\mathrm{m}^2$, 3 m height and thickness of walls and ceiling of 25 cm and 30 cm respectively collapses into a pile of rubble of height 1.5 m the degree of compression is about 40%, i.e., 40% of the space is occupied by rubble after the collapse.

2.3. Percentage of Materials

The quantity of each material, i.e., the volume of a given material with respect to V_{solid} depends on the building typolgy. In case of concrete buildings, the percentage has been determined according to the Italian rules for building construction it has been set to: 57% brick, 40% concrete, 3% reinforcement iron. For scenarios concerning antique stone buildings the materials considered are, instead, stone, construction sand and brick in respective percentages of 60%, 30% and 10%.

2.4. Graininess

The size of the blocks of homogeneous material is variable and uncertain. In case of old building, it corresponds to the size of stones used in the construction and it depends on building typology. Typically, in historic center of Italian and European towns, roughly squared stone blocks mixed with bricks and dressed stone blocks are used. Large squared stone blocks are used for quoins in both common buildings and mansions. In case of concrete buildings, the uncertainty of the size of homogeneous blocks are greater than that of old building because some structural parts of the building (e.g., reinforced concrete beam) may be collapsed intact while other parts (e.g., bricks) are crushed.

For these reasons the size of the single block is considered a variable of the model, similar scenarios having all the model parameters identical except for the size of the blocks are analyzed. Two different sizes are considered in order to analyze the effects that debris dimension has on the propagation of the electric field. In particular, cube blocks with side of 20 cm and 50 cm are considered.

2.5. Model Generation

Because of the extreme variety of scenarios in an actual collapse, a statistical analysis based on the generation of a large number of random models is required to characterize the propagation channel. A large amount of numerical data is necessary to obtain statistical significant results. A computer code able to generate automatically different random scenarios and to perform the electromagnetic analysis is developed. It is based on two simulation tools: CST Microwave Studio and Matlab.

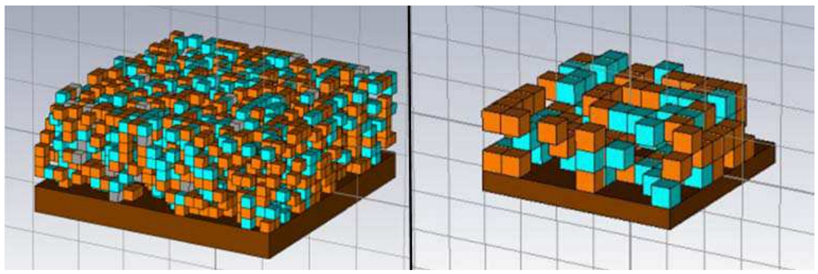
The FIT (Finite Integration Technique) solver of CST is used to perform the analysis of each random scenario. CST generates a file.mod (Model.mod) which contains all the simulation settings of a scenario, i.e., geometrical description of the scenario, materials properties, measurement unit, frequency range, field monitors, transmitted electric field intensity etc.. Instead of using the software graphical interface to generate that file, the template file is written as a text file using Matlab after generating the single random scenario.

A scenario consists of cubic blocks randomly arranged in an area of $25\,\mathrm{m}^2$ to form a heap 1.5 m high, the developed Matlab code uses a 3D matrix (A) of random elements (of dimensions $25\times25\times8$ for cubes with side 20 cm and $10\times10\times3$ in the case of cubes with side 50 cm) in which each element represents a cube of material. The type of material of each cube is determined taking into account the percentage of each material and the degree of compression of the rubble. In Table 2 an example of allocation of materials for representative scenarios of concrete building is shown. A variable q is considered, it can randomly assume values between 0 and 1 with uniform distribution. For each cube having indices (i, j, k) the value of q is randomly extracted, if $q \leq 0.012 = 3\%$ of 40% the PEC material is assigned to that cube, if $0.012 \leq q \leq 0.242 = 57\%$ of 40% brick properties are assigned, if $0.242 \leq q \leq 0.4 = 40\%$ of 40% the cube has the property of concrete otherwise it is made of air. At the boundary PML absorbing conditions are imposed, any cube made of PEC and located at the sides of the scenario are removed and replaced by air. Also the buried dipole is surrounded by air assuming it is placed in a void space inside the rubble. Once the matrix is generated, Matlab calculates the coordinates of each cube in the scenario and write the mod-file inserting in the header the absorbing boundary conditions, the calculation domain and the parameters of the mesh to be adopted and all other simulation parameters, then it continues with the description of the other structures involved (soil, cubes and dipole antenna). Fig. 1 shows two examples of scenarios obtained with the described method while Fig. 3 shows a layered scenario with interspaces randomly filled.

Finally, the Matlab code starts the running of a batch file, which launches the CST solver with the current generation of the mod-file. Once the electromagnetic simulation terminates the results

Table 2: Material allocation.

Matrix element value	Assigned material
$A(i,j,k) <= 0.012$	PEC
$0.012 < A(i,j,k) <= 0.242$	brick
$0.242 < A(i,j,k) <= 0.4$	concrete
$0.4 < A(i,j,k) <= 1$	air



(a) (b)

Figure 1: Random scenarios. Cubes with side of (a) 20 cm and (b) 50 cm. Colour: orange for brick, blue for concrete, gray for iron, brown for soil.

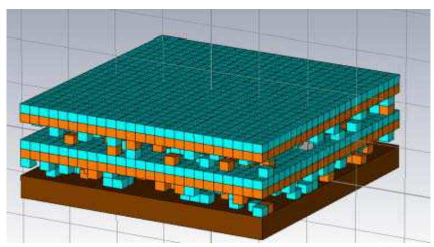


Figure 2: Layered model.

are saved, a new environment is made and a new simulation starts again with automatic process.

Three different frequencies are considered: 13 MHz 432 MHz and 900 MHz, buried dipole antenna is a short dipole at the frequency of 13 MHz and in a $\lambda/2$ dipole at the frequencies of 432 MHz and 900 MHz.

3. SIMULATION RESULTS

Aim of the work is the investigation of the possibility to localize a buried antenna starting from the analysis of the electric field on a plane located 0.5 m above the pile of rubble. The path loss and the phase of the received signal are evaluated at the points of that plane.

A virtual antenna is used at any receiving point. At 13 MHz ($\lambda = 23$ m) a short dipole of length 23 cm is used. It is characterized by a radiation resistance of

$$R_r = 80\pi^2 \left(\frac{l}{\lambda}\right)^2 = 0.08\Omega \tag{2}$$

and effective height

$$\underline{h}(\vartheta) = \frac{l}{2} sen(\vartheta)\, \underline{\hat{\vartheta}} \tag{3}$$

being ϑ the angle of the observation point with respect to the dipole axis.

The received power is therefore

$$P_R = \frac{1}{8}\frac{|V_a|^2}{R_r} \quad \text{with} \quad V_a = \underline{h}(\vartheta) \cdot \underline{E} \tag{4}$$

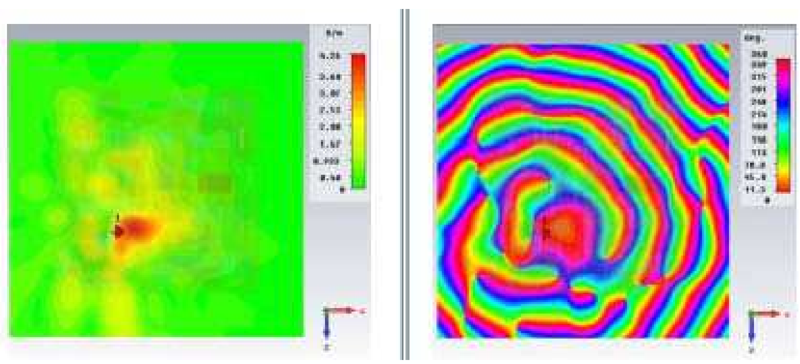
Being the power transmitted (P_T) by the buried dipole known, the path loss (PL) is calculated exploiting (4), i.e.,

$$PL = -10 \log \left(\frac{P_R}{P_T} \right). \tag{5}$$

At 432 MHz ($\lambda = 69$ cm) or 900 MHz ($\lambda = 33$ cm), instead, a virtual half wavelength ($\lambda/2$) dipole is considered, for which the radiation resistance is $Rr = 73.13\,\Omega$ and the effective height is calculated as

$$\underline{h}(\vartheta) = \frac{\lambda}{\pi} \frac{\cos\left(\frac{\pi}{2}\cos(\vartheta)\right)}{sen(\vartheta)} \underline{\hat{\vartheta}} \tag{6}$$

For a given realization of the scenario we obtain numerical data of the electromagnetic field inside and outside the rubble. In Fig. 3 it is shown, as an example, the obtained electric field at points of a plane placed 0.5 m above the rubble. It is obtained for rubble having DoC = 40%, size of the cube 20 cm and frequency 423 MHz. Both amplitude and phase are calculated in order to evaluate the possibility to detect the buried transmitting dipole by means amplitude and phase measurements. In the reported case, amplitude is stronger in the nearness of the vertical projection of the buried dipole while phase shows a characteristic behaviour made of concentric equi-phase lines (like wavefronts) centered in the nearness of the vertical to the transmitter.



(a) (b)

Figure 3: (a) Amplitude and (b) phase of electric field on a plane 0.5 m above rubble at 432 MHz, DoC = 40%, cube side = 20 cm.

The analysis of numerical data for different parameters of the scenario, in particular the frequency and the size of the cubes, allows us to have an in depth knowledge of the propagation inside that model of rubble. At lower frequency (i.e., 13 MHz) the map of field amplitude on a plane above the rubble shows a spot of strong field amplitude (like that of Fig. 2) but the phase has a coarse map because of the large length of the wavelength. Therefore amplitude measurements are more suited to be used for localization than phase measurements. At higher frequency (i.e., 900 MHz) instead the amplitude map shows different peaks of the maximum field spread all over the considered area. On the other hand the phase map preserves the almost circular equi-phase lines so that, at higher frequency, phase measurements appear more adequate for localization than amplitude measurements.

Considering the analysis by varying the size of the rubble, i.e., the size of the cube, it appears that larger is the size of the rubble lower are the spread of peaks of the maximum of the emerging field while the phase map is better represented by concentric equi-phase lines.

Here, we show results for four scenarios having different model parameters, in particular at the frequency of 432 MHz.

The first and second scenarios have DoC = 40% and rubble size 20 cm and 50 cm, the third scenario concerns DoC = 30% and rubble size 20 cm while the fourth scenario is a stratified model made up of four layers of homogeneous thickness (20 cm). Each layer consists alternately of concrete and bricks interspersed with layers where the ratio between materials and air is 20% (Fig. 2). This whole scenario has a ratio between full volume and total volume of 60%, is therefore characteristic of a situation in which the rubble are more compressed than in the other cases. For each type of scenario 30 realizations (i.e., simulations) are considered.

To have a quantitative analysis of the possibility to localize a buried transmitter using an amplitude map, the distance between the maximum of the electric field module or the maximum of

Table 3: Localization uncertainty.

scenario	variable	$\mathbf{e}_{\min}$ (cm)	$\mathbf{e}_{\text{avg}}$ (cm)	$\mathbf{e}_{\max}$ (cm)
1: DoC = 40% cube size 20 cm	Elettric field module	11	51	88
	Power flow module	12	52	106
2: DoC = 40% cube size 50 cm	Elettric field module	13	49	145
	Power flow module	11	49	115
3: DoC = 30% cube size 20 cm	Elettric field module	29	80	190
	Power flow module	24	73	188
4: DoC = 60% layered	Elettric field module	9	67	90
	Power flow module	14	67	139

the power flow module and the projection of the transmitting dipole position onto the observation plane, is determined. Table 3 shows the values of maximum, minimum (i.e., $e_{\max}$ and $e_{\min}$) and average value of the localization uncertainty. Note that there is not a simple relationship between the changing of the DoC of the scenario and the uncertainty of localization instead it seems to exist for the size of the rubble. In fact, smaller are the rubble larger is the uncertainty, probably because small debris entails a greater diffraction which gives and the occurrence of many local maxima that make the amplitude analysis less clear than in other cases.

Data relating to path loss are analyzed, the minimum of path loss is calculated on a plane 0.5 m above the rubble for each realization. Two different calculations are carried out (case 1 and case 2) which distinguish for evaluating the average and standard deviation of the path loss values. In case 1, the average is evaluated as the minimum value of the average matrix calculated over the entire observation plane for all simulations/realizations, in case 2 instead it is the average of the minimum values of path loss recognized in each matrix relative to a single simulation/realization. For the two average values the respective standard deviations are calculated.

The standard deviation is calculated as

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n}} \tag{7}$$

where x_i is the minimum path loss value for the current simulation/realization, $\bar{x}$ is the average (calculated in the two exposed ways), n is the total number of simulations considered for each scenario. In Table 4 the results obtained are shown. Similarly to the calculation of the uncertainty of localization the path loss is larger for smaller size of the cube rubble, evidently a stronger interaction of the electromagnetic wave with the rubble occurs.

In comparison to the measurements taken in real scenarios and published in [12, 13] the obtained results of path loss shown in Table 4 are greater. The discrepancy can be ascribed to the particular choice of the parameters of the considered scenarios (i.e., DoC, rubble size dielectric properties of materials as well as the percentage of the materials). Evidently, a tuning of the parameters to obtain numerical results aligned to measured data is possible but a lot of carefulness is necessary in pursuing that objective for not specializing the tuned scenario to a specific measurement site. An additional measurement campaign is therefore necessary to collect experimental data from a large number of different sites.

Table 4: Path loss calculation.

scenario		avg (dB)	σ (dB)
1: DoC = 40% cube size 20 cm	Case 1	63.04	7.88
	Case 2	58.79	2.83
2: DoC = 40% cube size 50 cm	Case 1	48.65	7.63
	Case 2	44.85	3.84
3: DoC = 30% cube size 20 cm	Case 1	59.08	8.06
	Case 2	54.81	3.22
DoC = 60% layered	Case 1	61.56	7.71
	Case 2	57.32	2.35

4. CONCLUSION

This work has focused attention on a transmission medium particularly complex and difficult to characterize as building rubble. In order to analyze a large number of scenarios, and then consider many of the possible real situations, random models are developed. The model are automatically generated allowing to obtain a large number of data for a significant statistical analysis. The electromagnetic simulation are performed in the time domain in order to determine the attenuation properties of the transmission medium and its effects on the electric field characteristics.

The study highlights the fundamental importance of the rubble dimension rather than the specific materials involved. Furthermore it shows that it is possible to determine the position of a buried transmitting antenna analyzing the amplitude and the phase of the electric field and the power flow module.

REFERENCES

1. Doroodgar, B., M. Ficocelli, B. Mobedi, and G. Nejat, "The search for survivors: Cooperative human-robot interaction in search and rescue environments using semi-autonomous robots," *2010 IEEE International Conference on Robotics and Automation Anchorange Convention District*, Anchorage, Alaska, USA, May 3–8, 2010.
2. Yokokohji, Y., M. Kurisu, S. Takao, Y. Kudo, K. Hayashi, and T. Yoshikaww, "Constructing a 3-D map of rubble by teleoperated mobile robots with a motion canceling camera system," *Proceedings of the 2003 IEEE/RSJ Intl. Conference on Intelligent Robots and Systems*, Las Vegas, Nevada, Oct. 2003.
3. Wiesner, A., "CW radar based vital signs detection," *Proceedings of the 39th European Microwave Conference*, 2009.
4. Ivashov, S. I., V. V. Razevig, A. P. Sheyko, and I. A. Vasilyev, "Detection of human breathing and heartbeat by remote radar," *PIERS Proceedings*, Pisa, Italy, Mar. 28–31, 2004.
5. Bimpas, M., K. Nikellis, N. Paraskevopoulos, D. Economou, and N. Uzunoglu, "Development and testing of detector system for trapped humans in building ruins," *33rd European Microwave Conference*, Munich, 2003.
6. Yarovoy, A. G., L. P. Ligthart, J. Matuzas, and B. Levitas Geo Zondas, "UWB radar for human being detection," *IEEE A&E System Magazine*, Mar. 2006.
7. Zaikov, E., J. Sachs, M. Aftanas, and J. Rovnakova, "Detection of trapped people by UWB radar," 2008.
8. Filali, B., F. Boone, J. Rhazi, and G. Ballivy, "Design and calibration of a large open-ended coaxial probe for the measurement of dielectric properties of concrete," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 56, No. 10, Ottobre, 2008.
9. Pana, F., "Measurement and modeling of propagation losses in brick and concrete walls for 900-MHz band," *IEEE Transactions on Antennas and Propagation*, Vol. 51, No. 1, Gennaio, 2003.
10. Oestges, C., B. Montenegro-Villacieros, and D. Vanhoenacker-Janvier, "Modeling propagation into collapsed buildings for radio-localization-based rescue search mission," *IEEE*, 978-4244-3647-7/09/$25.00 ©, 2009.
11. Di Carlofelice, A., E. Di Giampaolo, M. Elaiopoulos, M. Feliziani, M. Roselli, and P. Tognolatti, "Localization of radio emitters into collapsed buildings after earthquake: Measurements of path loss and direction of arrival," *2012 International Symposium on Electromagnetic Compatibility (EMC EUROPE)*, 1–6, Sep. 17–21, 2012.
12. Di Carlofelice, A., E. Di Giampaolo, M. Feliziani, and P. Tognolatti, "Experimental characterization of electromagnetic propagation under rubble of a historic town after disaster," *IEEE Transactions on Vehicular Technology*, 2014, DOI: 10.1109/TVT.2014.2346580.
13. Teggi, S. and T. di Laurea, "Metodi geofisici," Facoltà di Ingegneria-Università degli studi di Modena e Reggio Emilia, A.A., 2007/2008.
14. Martinez, B., "Modeling dielectric-costant values of geologic materials: An aid to ground-penetrating radar data collection and interpretation," *Current Researc in Earth Sciences*, 247, Part I, Bulletin, 2001.
15. Del Conte, A., "Il radar penetrante (GPR)," *Artemis Diagnostica Edilizia*, 22, Ancona, Gennaio, 2004.
16. Philippakis, C. Martel, and D. Kemp, "Application of FSS structures to selectively control the propagation of signals into and out of buildings," *ERA Technology*, 1–54, Febbraio, 2004.