Large-Scale Fading Model for Mobile Communications in Disaster and Salvage Scenarios

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***Abstract*—Within a running project, I-LOV [1], wireless communication channel model for mobile radio propagation in disaster and salvage scenarios is developed. This contribution focuses on a semi-empirical large-scale fading (LSF) model, which is able to estimate signal power loss between base station and mobile phone under debris. Due to multitude of diverse materials appearing in burying scenarios, the signal loss factor varies heavily depending on electromagnetic properties of involved materials. Additionally, highly variable shape and dimension of rubbles impact strongly the loss factor. Besides numerous LSF models investigated in urban environments, only a few are in ruins. This paper presents a novel modeling concept of LSF in catastrophe scenarios. The proposed LSF model handles the radio propagation way in two parts: outside ruins and through the ruins. Measurements have been conducted at GSM 900 and GSM 1800 bands in collapsed buildings of stratified rubbles, as well as in an avalanche scenario. The model predication fits the measured data well.**

Keywords-mobile radio channels; large-scale fading model; path loss; collapsed buildings; avalanches

I. Introduction

The BMBF[2] project "I-LOV" focuses on the development of an intelligent safeguarding localization system for search and rescue application of trapped and buried people. Among diverse detecting modules in this system, our team are working on positioning of mobile station (MS). Experiences show that in a disaster situation 80 % of buried people have personal mobile phones. Hence a located mobile phone in the ruins indicates a high possibility that a buried person is near it.

In the "I-LOV" project base stations (BSs) are planned for real rescue operation to build a local network covering the ruin area. Different locating approaches like time-difference-of-arrival (TDOA) techniques or signal-strength methods will be integrated in the BSs. Both the positioning algorithms and the plan of building up a local cell requires particular knowledge about the characteristics of the propagation channel. One of the most important characteristics is the signal power attenuation along the propagation path, which is caused by free space propagation, diffraction, reflection and scattering. The average power attenuation is defined as large-scale fading (LSF) or path loss (P_L). In mobile radio communications, conventional studies of LSF model are performed in typical environments like urban [1, 2, 3, 4], outdoor-to-indoor [4, 5, 6] and indoor [4, 7, 8, 9]. A novel aspect of disaster and salvage scenarios, like collapsed buildings and avalanches, is investigated in this work. Because of multitude of diverse materials appearing in burying scenarios, P_L varies heavily depending on electromagnetic properties of involved materials. Furthermore, due to the highly variable shape and dimension of rubbles, P_L changes from one position to another under the same ruin. Hence the proposed LSF model has been developed as a semi-empirical model, i.e. the model is based on statistical properties of measurement data and deterministic aspects of geometry information in ruins. With the idea from the outdoor-to-indoor model in [4], the entire path loss between the MS and BS antenna is determined with two parts: outside ruins and through the ruins. For each part a path loss model depending on distance and frequency has been investigated. Measurements were conducted with a vector network analyzer (VNA) at GSM 900 and GSM 1800 bands in collapsed building of stratified rubbles, as well as in an avalanche scenario. The model predication fits the measurement data well.

II. Large Scale Fading Model

In contrast to conventional path loss models, debris is a great obstacle between BS and MS antenna, which could cause heavy signal power attenuation. The outdoor-to-indoor model mentioned in COST-231 [4] contributed idea for LSF model in catastrophe scenario. In this model (see Fig. 1) the signal propagation path is divided in two parts: from BS to the external wall, and from the external to MS through several internal walls. The radio waves transmitted by the BS penetration the external wall at the point which is nearest to the MS [6]. The same path partition is in the provided model implemented. So the following expression is yielded:

$$P_L = A_{\text{free\_space}} + A_{\text{ruin}}, \tag{1}$$

[1] Further information about I-LOV: www.i-lov.org
[2] BMBF: German Federal Ministry of Education and Research

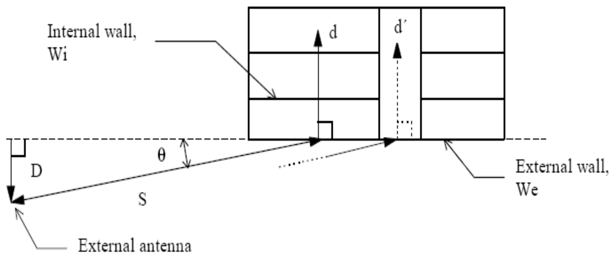


Figure 1. Outdoor-to-indoor model introduced in COST-231 [4]

Figure 2. Large-scale fading model for disaster and slave scenarios

where $A_{\text{free\_space}}$ is the signal power loss caused by free space propagation, i. e. from BS antenna to exterior side of the ruins. A_{ruin} is the physically and statistically computed signal attenuation through the ruins. These two propagation losses are calculated individually.

A. Free Space Propagation Loss

Local GSM networks are planed in real rescue missions. For cell planning it is necessary to conduct a system specification with burying environments. According to the experience from THW[3], the intended radio cells can be classified as outdoor microcells or picocells. As an example we consider the misfortune in Cologne (Germany) on 3 March 2009, as the historical archive of the city collapsed. The rescue area is about 40 m * 70 m, which can be treated as outdoor picocell situation.

The Walfisch-Ikegami propagation model [1, 2, 4] is suitable for our application. This empirical model has been proposed for calculating path loss in urban for small cells and is presented as follows:

$$P_{\text{NLOS}} = -55,9 + 38 * \log_{10}(d) + (24,5 + 1,5 * f_c / 925) * \log_{10}(f_c) \tag{2}$$

$$P_{\text{LOS}} = \text{-}35,4 + 26 * \log_{10}(d) + 20 * \log_{10}(f_c) \tag{3}$$

[3] THW: the Germany Federal Agency for Technical Relief

where d is the distance in m and bounded from 20 to 5000 m, and f_c is the carrier frequency in MHz and limited to 2000 MHz. LOS (line-of-sight) is defined for the case that the radio waves propagate in a straight line. This case occurs frequently in rescue scenarios.

B. Ruin Loss

To predict signal attenuation through ruins, a simplified model is developed for stratified debris structure. This structure is simulated with parallel layered rubbles (see Fig 3). Each layer can be characterized by its thickness and the involved material. Assuming a linear attenuation behavior through n layers, the path loss model can be described with the following mathematical formula:

$$A_{\text{ruin}} = \sum_{n=1}^{N} a_n \cdot h_n \;([a_n] = \text{dB}/\text{m}, [\text{h}_n] = \text{m}), \tag{4}$$

where a_n is the signal power attenuation through n'th layer and h_n is the layer thickness. The parameter a_n dependents on the electromagnetic properties of the associated material. The attenuation factors of frequently used building materials, like ferroconcrete or concrete, have been reported in several literatures. However, we have conducted our own measurements to validate them. The result is presented in section V part A. The parameter h_n is determined according to the actual construction of the observed debris structure.

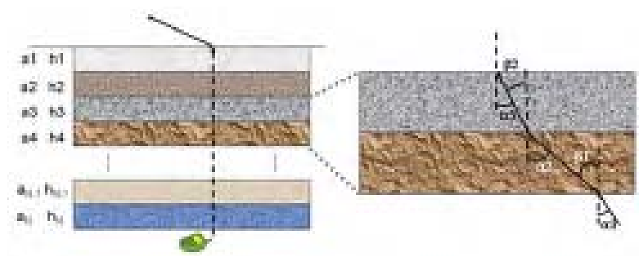


Figure 3. Geometry of pararell straified debris structure

III. MEASUREMENT DESIGN

To measure the average attenuation through ruins, a vector network analyzer (VNA, 0.3-8.5 GHz) was employed. The measurement setup is shown in Fig 4.

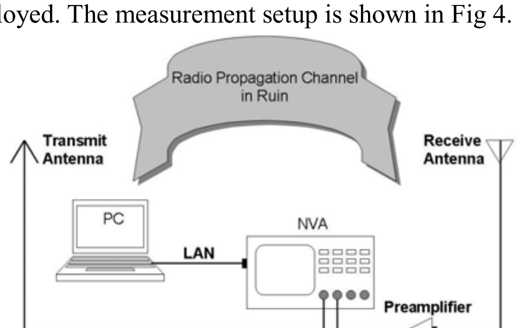


Figure 4. Block diagram of the measurement system

A LabView program on PC gives command to VNA to capture frequency response at the frequency rang of 500-3000 MHz and gets the measured data back with LAN connection. A preamplifier was used, since the attenuation factor of the channel was out of the VNA's dynamic range. The transmit and receive antennas were two identical logarithmic periodic broadband antennas with an isotropic gain of 5±1 dB. The half power E pattern angle is in range of 76°-82° and the H pattern angle is 125°-145°. One of the antennas was placed outside the ruin and mounted on the top of a 6 m high antenna mast. The other antenna was placed in tunnels under the ruins. The distance between the antennas varies from 30.9 to 39.4 m. Furthermore, both of the antennas were horizontally polarized and arranged towards each other.

The purpose of this work is to determine the radio propagation channel in ruins. However the measured data contain information through several channels, since between the two ports of the VNA there were cables, preamplifier and the antennas. Hence calibration was required to diminish the effect of unexpected channels. The method of calibration without antennas was performed in this work. System response (H_{system}) was measured, as the antennas were removed and the cables were connected with an attenuator (-30 dB). The attenuator was used to protect the VNA against high input voltage caused by the preamplifier. This attenuation factor has then been compensated in the computation of P_{L}. So the calibrated $H(k)$ is given by:

$$H_{\text{calibrated}}(k) = \frac{H_{\text{measured}}(k)}{H_{\text{system}}(k)}. \tag{5}$$

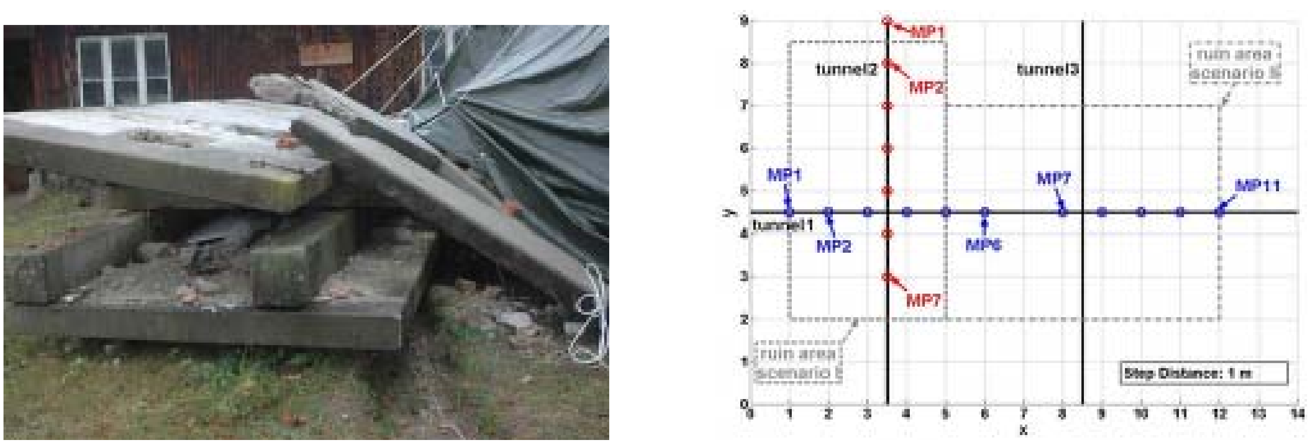
It is emphasized that $H_{\text{calibrated}}(k)$ is the instantaneous frequency response of the ruin channel within the behavior of the antennas.

Figure 5. Artificially constructed avalanche in the black forest

IV. Measurement Campaign

To estimate the signal attenuation through collapsed buildings, measurements were conducted on a testing area in a forest outside the city of Karlsruhe. Colleagues from the Institute for Technology and Management in Construction (TMB) at the Karlsruhe Institute of Technology (KIT) have designed and constructed the ruins under real collapsed building conditions. As a pre-work, they have built several tunnels for transporting antennas under the artificial ruins. Tunnel 1 has a length of 14 m. Tunnel 2 and tunnel 3, which cross tunnel 1 separately, are both 9 m long. All of them have a depth of 30-40 cm and a width of 60-70 cm. The measured debris with stratified structure is shown in Fig. 6 (a). It consists mainly of ferroconcrete walls. The structure simulates damage scenario of halls and ferroconcrete buildings. The entire height of this ruin is max. 110 cm and its width is about 7 m. Fig 6 (b) shows the measurement positions in transport tunnels with coordinate information.

There were another measurements conducted for avalanche scenarios. A heap of fresh snow was build up by THW workers (see Fig 5). A tunnel for transporting antenna was also constructed. The distance between the transmit and receive antenna is about 9 m.



(a) (b)

Figure 6. Measurement area descriptions: (a) Artificially reconstructed collapsed buildings with stratified structure; (b) The antenna positions in the transport tunnels. The area marked with grey dashed line and labeled as "scenario I" is the ruin area shown in (a).

V. Analysis of Measurement Results

A. Ferrorconcrete Wall Attenuation

The measured collapsed structure consists mainly of ferroconcrete walls. Hence, we have measured the power attenuation factor of ferroconcrete to determine the model parameter a_n. The measurements have token place in the basement of IMTEK building. The measurement system is similar like shown in Fig 4. Certainly, instead of ruins a ferroconcrete wall was measured. The signal power attenuation through the wall is calculated using:

$$a_{\text{wall}}(f) = H_{\text{withWall}}(f) / H_{\text{withoutWall}}(f), \tag{6}$$

where H_{withwall} is the frequency response (FR) measured with the wall and $H_{\text{withoutWall}}$ is FR measured in LOS situation. a_{wall} was smoothed with a moving-average filter and averaged over several measurements. The results are presented in Tab. I, as well as some results from other literatures. Due to different thickness of the measured objects, the unit of attenuation factors was converted from dB to dB/cm.

TABLE I. Attenuation Factor of Ferroconcrete

	GSM 900			GSM 1800		
	(a)	*(b)*	*(c)*	*(a)*	*(b)*	*(c)*
$a_{\text{ferroconcrete}}$[dB/cm]	0.42	-	0.41	0.65	0.4	0.66

(a) IMTEK; (b) Jenvey [10]; (c) Rauli & Moldan[11]

Due to the different structure of the test specimens, our measurement results differed from the results of [10] at GSM 1800. But they are consistent with the results from [11]. More measurements should be conducted in the future to verify the present attenuation factors. Additionally, more building materials will be investigated.

B. Path Loss through collapsed buildings

To estimate P_L the calibrated frequency response $H_{\text{calibrated}}(f)$ was calculated for each measurement and the results were finally smoothed using a moving-average filter. The standard deviation between $H_{\text{calibrated}}(f)$ and its averaged data varies from 8.7 to 9.9 dB.

The distance between the BS antenna and the penetration point on the exterior side of the ruins is needed to determine $A_{\text{free\_space}}$. As mentioned in section II, the penetration point is defined at the point which is closest to the antenna under the rubbles. Due to the beam direction of the antenna the actual measured positions were moved 30 cm. Finally the following points are token into account to estimate the attenuation under the stratified structure: MP1 to MP4 in tunnel 1 and MP1 to MP7 in tunnel2. The corresponding ruin thickness ($h_{\text{ferroconcrete}}$) at each point is listed in Tab. II. The model predicted ruin attenuation (using $A_{\text{ruin}} = a_{\text{wall}} * h_{\text{ferroconcrete}}$) and the measured attenuation ($A_{\text{ruin}} = P_L - A_{\text{free\_space}}$) are plotted in Fig 7 and Fig 8.

TABLE II. The Thickness of the measured Ruins

Tunnel 1	**MP1**	**MP2**	**MP3**	**MP4**	**MP5**		
$h_{\text{ferroconcrete}}$ [cm]	0	70	65	60	60		
Tunnel 2	**MP1**	**MP2**	**MP3**	**MP4**	**MP5**	**MP6**	**MP7**
$h_{\text{ferroconcrete}}$ [cm]	0	60	60	60	70	50	20

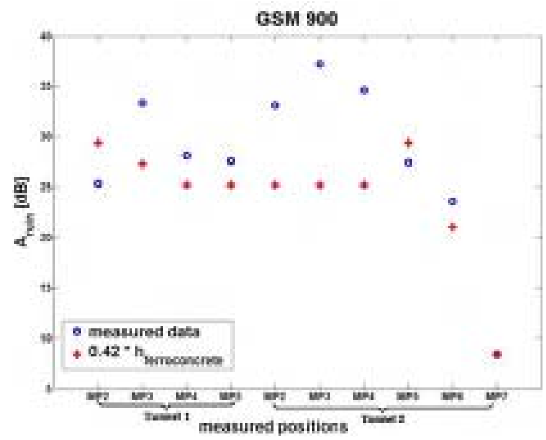


Figure 7. Attenuation factor of ruins (A_{ruin}) for signals of 900 MHz

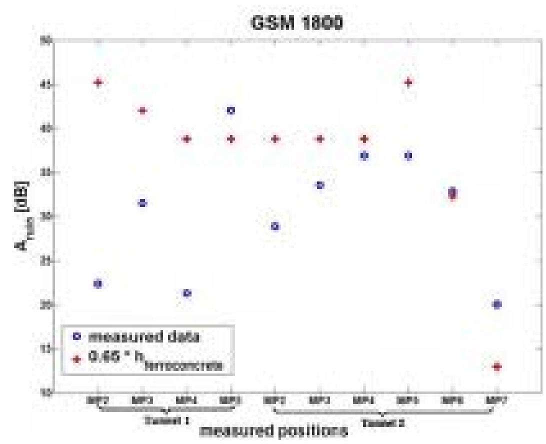


Figure 8. Attenuation factor of ruins (A_{ruin}) for signals of 1800 MHz

In Fig 7 the predicted attenuation is close to the measured data in tunnel 1, but far away from MP2 – MP4 in tunnel 2. However Fig 8 shows large disparity in tunnel 1. The deviation between the measured data and the model predications should be caused by the actual signal propagation path through the ruins, because the ferroconcrete walls were not placed parallel with each other. Furthermore, there are holes, dust and broken stones at some places inside the debris. This is also not calculated in the model. The deviation could also caused by the antenna polarity. A comparison of A_{ruin} between measurements and model predications is shown in Tab. III. The simplified model performs better by signals of 900 MHz than of 1800 MHz due to the longer wave length at the low frequency.

TABLE III. COMPARISON OF A_{ruin} BETWEEN MEASURMENTS AND MODEL PREDICATIONS

GSM 900 [dB]			**GSM 1800 [dB]**		
(a)	***(b)***	***(c)***	***(a)***	***(b)***	***(c)***
27.86	24.15	4.92	30.60	37.12	8.71

(a) average of measured data; (b) average of model predications; (c) average deviation between measured data and model predications

C. Path Loss through Snow

To estimate the power attenuation through snow, similar set up like the ferroconcrete measurement (see section A) was conducted. Frequency responses H_{snow} were captured, as one antenna was placed inside the snow heap. $H_{\text{free\_space}}$ was for the LOS case that no snow was between the transmit and receive antennas. Therefore the attenuation factor through snow can be calculated as:

$$a_{\text{snow}}(f) = H_{\text{snow}}(f) / H_{\text{free\_space}}(f). \tag{7}$$

The results show that signals at 900 MHz have just a few power loss (under 0.1 dB/m) through the snow, and signals at 1800 MHz have a little more but also small attenuation (under 0.2 dB/m). These results are consistent with many literatures, for example [12].

VI. CONCLUSION AND OUTLOOK

In this work a semi-empirical large-scale fading (LSF) model has been investigated, which is able to estimate signal loss between base station and mobile phone under debris at GSM 900 and GSM 1800 frequency bands. The proposed model consists of two parts. One part is the attenuation along the LOS path between the base station and the penetration point of the exterior side of ruins, namely $A_{\text{free\_space}}$. It is calculated with the Walfish-Ikegami model. The other part is the penetration loss through the debris, denoted as A_{ruin}. For the second part, a simplified model was introduced. This model bases on an ideal parallel stratified ruin structure and an assumption of linear attenuation behavior through multilayer in the structure. Measurements have been conducted in two disaster scenarios: collapsed buildings and avalanche. The average attenuation through the collapsed buildings (consisting of ferroconcrete walls) was measured at 27.86 dB by GSM 900 and 30.60 dB by GSM 1800. The model gives an average loss with 24.15 dB and 37.12 dB at GSM 900 and GSM 1800. A worse performance at the high frequency is also shown by the average deviation between the measured data and the model predications. This is due to the shorter wave length of GSM 1800, which could cause longer propagation path through the ruins. The snow attenuation has been also researched in the avalanche scenario. The small power loss measured in this work shows that by fresh and relative dry snow the attenuation factor can be ignored.

As future work, we will take more measurements with smaller separated distance under the collapsed ferroconcrete walls to evaluate the measurements in this work and to verify or optimize the simplified model. An omnidirectional antenna is also good for the further experiments, because it simulates the mobile phone antenna. To complete the proposed LSF model, another collapsed structure, namely chaotic structure, should be researched. In such structure more broken stones can appear and the materials don't lie parallel on each other. More scattering and diffraction phenomena will rise up.

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REFERENCES

[1] J. Walfisch and H. L. Bertoni, "A theoretical model of UHF propagation in urban environments," IEEE Trans. on Antennas and Propagation, vol. 36, no. 12, pp.1788-1796, Dec. 1988

[2] F. Ikegami, S. Yoshida and M. Umehira, "Propagation factors controlling mean field strength on urban streets," IEEE Trans. on Antennas and Propagation, vol. 32, no. 8, pp. 822-829, August 1984

[3] Y. Oda, R. Tsuchihashi, K. Tsunekawa and M. Hata, "Measured path loss and multipath propagation characteristics in UHF and microwave frequency bands for urban mobile communications," IEEE Veh. Technol. Conf., vol. 1, no. 53ND, pp. 337–341, 2001.

[4] COST-231 final report, http://www.lx.it.pt/cost231/, COST (europäische Forschungszusammenarbeit), Chapter 4, 1999.

[5] R. Hoppe, G.Wolffe, and F. M. Landstorfer, "Measurement of building penetration loss and propagation models for radio transmission into buildings," in IEEE Veh. Technol. Conf., pp. 2298–2302, September 1999.

[6] Y. Miura, Y. Oda, and T. Taka, "Outdoor-to indoor propagation modelling with the identification of path passing through wall openings," PIMRC 2002, Lisbon, September 2002.

[7] S. Y. Seidel and T. S. Rappaport, "914 MHz Path Loss Prediction Models for Indoor Wireless Communications in Multifloored Buildings," IEEE Transaction on Antennas and Propagation, vol. 40, No. 2, February 1992.

[8] S.S. Ghassemzadeh, L. J. Greenstein, A. , T. Sveinsson and V. Tarokh "An Empirical Indoor Path Loss Model for Ultra-Wideband Channels," KICS Journal of Communications and Networks, vol. 5, No. 4, pp. 303–308, December 2003.

[9] D. Cassioli, M. Z. Win and A. F. Molisch, "A statistical model for the UWB indoor channel," in Proc. of IEEE Vehic. Tech. Conf., vol. 2, pp. 1159-1163, Greece, May 2001.

[10] S. Jenvey, "Ray Optics Modelling for Indoor Pro-pagation at 1.8 GHz," IEEE 44th Vehicular Tech-nology Conference Proceedings, pp. 1750 – 1753, 1994.

[11] P. Pauli and D. Moldan, "Reduzierung hochfre-quenter Strahlung – Baustoffe und Abschirmmate-rialien," 2. edition, pp. 15, 2003.

[12] A. Denoth, "Snow Dielectric Measurements", Adv. Space Res., vol. 9, No. 1, pp. (1)233– (1)243, 1989.