Investigation and Adaptation of Signal Propagation Models for a Mixed Outdoor-Indoor Scenario Using a Flying GSM Base Station

Alina Rubina, Oleksandr Andryeyev, Mehdi Harounabadi, Ammar Al-Khani, Oleksandr Artemenko(✉), and Andreas Mitschele-Thiel

Integrated Communications System Group, Ilmenau University of Technology, 98693 Ilmenau, Germany
{alina.rubina,oleksandr.andryeyev,mehdi.harounabadi, ammar.al-khani,mitsch}@tu-ilmenau.de, lestoa@gmail.com

Abstract. In this paper, we consider a disaster scenario where a Micro Aerial Vehicle (MAV) is flying around the urban area and tries to localize wireless devices such as mobile phones. There is a high chance of those devices being in the vicinity of their human owners. Fast and simple approach to map the received signal strength to distance is the Received Signal Strength Indicator (RSSI). The more accurate mapping ensures higher localization accuracy. As a consequence, an accurate signal propagation model is required.

The Free Space model, ITU indoor and outdoor model, SUI model, Hata model, COST-231 Hata model and Log-distance model have been chosen to be investigated in this work. The goal was to determine whether analytically chosen models fit to our scenario, as well as develop a suitable model for outdoor-indoor scenario. A real-world experiment was carried out to collect RSS measurements. An MAV was placed outside of a building while mobile phones were located inside a building. A measure for the evaluation was a root mean square error (RMSE).

The main contribution of this paper is an adapted log-distance model for GSM which is suited for outdoor-indoor scenario with the RMSE value of 6.05 m. The ITU indoor model represents the second best fit to our measured data with the RMSE value of 6.3 m.

Keywords: MAV · Signal propagation models · Quadrocopter · GSM · Log-distance model

1 Introduction

In order to predict radio propagation behavior, different signal propagation models have been developed as the low-cost, convenient and suitable alternative to site measurements, since the later approach is expensive and complex [1]. Today several models have emerged for indoor and outdoor environments in urban, suburban and rural areas. The nature of those areas plays a significant role

Y. Zhou and T. Kunz (Eds.): ADHOCNETS 2016, LNICST 184, pp. 128–139, 2017.
DOI: 10.1007/978-3-319-51204-4_11

in the development of signal propagation models. Predicting the behavior of a wireless signal can be limited due to the following reasons: (1) distance between a transmitter and a receiver ranges from a couple of meters to few kilometers; (2) thickness of walls in a building can significantly affect the signal propagation; (3) the environment in which the signal propagates is usually not known [2].

A signal propagation model can be used to map received signal strength (RSS) to the distance. This mapping is crucial for localization purposes, when a technique called Received Signal Strength Indication (RSSI) is used. The more accurate the model is, the higher localization accuracy can be achieved. Other techniques, such as the Time of Arrival (TOA), Time Difference of Arrival (TDoA) and Angle of Arrival (AoA) can also be applied. However, those methods usually require additional hardware and precise time synchronization [3].

In this work, we consider a disaster scenario where the communication infrastructure has been ruined. As a consequence, victims of the disaster will not be able to make a call or send a message. A Micro Aerial Vehicle (MAV) flies around this area and locates mobile devices which could be in the vicinity of their human owners. We call this scenario – mixed outdoor-indoor, as mobile phones are inside a building and the MAV is flying outside.

For the development of a signal propagation model, we have chosen the GSM standard, as it is more reliable than the Wi-Fi network. Authors in [4] have observed that a GSM signal is more stable over time, than a Wi-Fi signal. Also, the bandwidth of the GSM channel is 200 KHz [5]. In contrast, the bandwidth of the Wi-Fi channel is 22 MHz and the channels are overlapping [6]. As a result, the interference in Wi-Fi channels can be significant.

Moreover, as previously stated, we are considering a disaster scenario in which it cannot be guaranteed that all mobile devices are running Wi-Fi access points. Whereas in the GSM network, mobile nodes will automatically perform the International Mobile Subscriber Identity (IMSI) attach procedure when they detect a network they can connect to [7]. There exist several propagation models in the literature [8–11] for calculating distance using RSS values, that were measured in a GSM network. However, none of them suit our purposes for the following reasons: (1) our scenario is unique and considers mixed communication between an indoor and an outdoor environment, while the most of models consider either an indoor or an outdoor scenario; (2) physical parameters of previous approaches do not fit our work, e.g., different receiver and transmitter heights, low transmitted power (6 dBm in our case); (3) necessity for the accurate RSS to distance mapping, as this directly affects localization accuracy. Therefore, a measurement campaign was performed according to our scenario to modify log-distance signal propagation model. The rest of the paper is organized as follows. In Sect. 2, an overview of existing models is given. Section 3 describes the conducted real-world experiment to collect RSS values. In Sect. 4, we present a developed model, as well as a comparison to the existing ones. Finally, Sect. 5 concludes the paper.

2 State of the Art

Path loss or path attenuation is a reduction in the power density of an electromagnetic wave as it propagates through space [8]. The signal propagation models describe how the path loss is dependent on path attenuation factor, transmitter antenna height, receiver antenna height, distance, operating frequency, etc. All models are designed using different assumptions and experimental data, obtained in the field. Therefore, a model should be carefully chosen in order to fulfill needs of a specific scenario.

Fingerprinting represent another very popular solution for the localization. However, the fingerprint technique represents an unstable solution for indoor scenarios and requires a priori knowledge about the site. Every small change in the environment causes drastic changes in the database of fingerprints. Therefore, it is essential to update the database frequently [12]. As a result, we will not follow this method in our work. In contrast, log-distance path-loss models are much less susceptible to changes in the environment and produce more stable results.

The most well-known signal propagation models that can be applied for a mixed outdoor-indoor scenario, where the transmitter is a flying GSM base station, are summarized in Table 1. As follows a list of used variables and constants is given:

- λ is a wavelength in meters,
- f is a frequency in MHz,
- γ is a path loss exponent,
- d is a distance between a transmitter and a receiver in meters,
- h_t is a transmitter antenna height above ground level in meters,
- h_r is a receiver antenna height above ground level in meters,
- X_σ represents a Gaussian random variable with zero mean and standard deviation of σ dBm and denotes shadow fading [13],
- P_{r_0} is a signal strength at 1 m from the transmitter,
- X_h is a correction factor for receiving antenna height,
- S is a correction factor for shadowing in the range between 8.2 and 10.6 dBm [14],
- $d_0 = 100$ m in the case of SUI model,
- L_f is a floor penetration loss factor in dB,
- n is a number of floors between the transmitter and the receiver,
- L_{out} is an outdoor path loss,
- L_{tw} is through-wall penetration loss,
- α is an attenuation coefficient for indoors (0.5),
- d_{in} is an indoor distance from wall to a receiver in meters,
- d_{out} is a distance from a transmitter to the wall next to the receiver in meters,
- L_0 is a loss in the free space,
- Q represents a field amplitude factor,
- L_{rts} is a roof to street diffraction loss,
- L_{msd} is a multiscreen diffraction loss.

Free space model is one of the most basic and well-known models for predicting path loss. The main limitation of this model is consideration of a line-of-sight path through free space without any reflection or diffraction effects which are present in our scenario [13].

Another well-known model is the log-distance model [15]. As can be seen in the respective equation from Table 1, it is a general model and thus is suitable for a variety of scenarios. This implies the main disadvantage of the log-distance model - tuning is required for each scenario in order to provide accurate results.

IEEE 802.16 Broadband Wireless Access working group proposed the standards for the frequency band below 11 GHz containing the channel model developed by Stanford University, namely the Stanford University Interim (SUI) model [16]. The SUI model has limitations, namely minimal antenna heights and transmission distance, which can lead to a significant accuracy reduction in the considered scenario due to the small altitude and transmission power of a flying GSM base station.

Table 1. The most well-known signal propagation models.

Title	Signal model	Frequency range [MHz]	Environment
Free space model [13]	$L = 32.44 + 20\log_{10}d + 20\log_{10}f$	NA	Outdoor
Log-distance path loss model [13]	$L = P_{r_0} - 10\gamma\log_{10}d + X_\sigma$	NA	Outdoor/ Indoor
SUI model [14]	$L = 20\log_{10}(\frac{4\pi d_0}{\lambda}) + 10\gamma\log_{10}(\frac{d}{d_0}) + X_f + X_h + S$	2500–2700	Outdoor/ Indoor
Hata model [8]	$L_{50}(urban) = 69.55 + 26.16\log_{10}f_c - 13.82\log_{10}h_t - a(h_r) + (44.9 - 6.55\log_{10}h_t)\log_{10}d$	150–1500	Outdoor/ Indoor
COST-231 Hata model [9]	$L_{50} = 46.3 + 33.9\log_{10}f - 13.82\log_{10}h_t - ((1.1\log_{10}f - 0.7)h_r - (1.56\log_{10}f - 0.8)) + (44.9 - 6.55\log_{10}h_t)\log_{10}d + c_m$	1500–2000	Outdoor/ Indoor
Walfisch and Bertoni model [10]	$S = L_0Q^2L_{rts}$	800–2000	Outdoor/ Indoor
Walfisch and Ikegami model [11]	$L_b = L_0 + L_{rts} + L_{msd}$	800–2000	Outdoor/ Indoor
ITU indoor short-range model [17]	$L = 20\log_{10}f + \gamma\log_{10}d + L_f(n) - 28$	900–100000	Indoor
ITU outdoor short-range model [18]	$L = L_{out}(d_{out} + d_{in}) + L_{tw} + \alpha d_{in} + X_\sigma$	900–100000	Outdoor

One of the most widely used models for predicting path loss in mobile wireless systems is the Hata model (also known as Okumura-Hata model) [19]. The Hata model is not designed for frequencies beyond 1500 MHz. Moreover, it is assumed that the transmitter antenna is located at least 30 m above the ground level, which is not always the case for a flying GSM base station.

In order to overcome the main limitation of this model, namely support for frequencies beyond 1500 MHz, a modified model, called COST-231 Hata, was proposed in [9]. Nevertheless, COST-231 Hata model still assumes that the transmitter antenna height is 30 m or more.

COST-231 project proposed models to consider buildings in the vertical plane between a transmitter and a receiver - Walfisch and Bertoni, Walfisch and Ikegami models [10,11]. The application of these two models is limited to the case when the transmitter is mounted above the rooftop levels of tall buildings. Our scenario has different assumptions and due to this fact we will not investigate these models in details.

The International Telecommunication Union (ITU) proposed an indoor propagation model [17]. According to [17], this model can be used in case of a coexistence in both indoor and outdoor environments. However, to apply this model, the floor penetration loss factor and the number of floors between the flying base station and the mobile phone should be known, which is not the case in a disaster scenario. ITU indoor short-range propagation model is designed to be used mainly for predicting signal propagation in indoor environments, so it should be evaluated in our mixed outdoor-indoor scenario.

For the scenarios where both indoor and outdoor conditions exist, ITU proposed the outdoor short-range propagation model [18]. It is assumed that the receiver is most likely to be held by a pedestrian, who can travel inside and outside of the building. The coefficients for different environments can be found in [17]. This model consists of many special cases for different scenarios. In a disaster scenario, where precise characteristics of the environment are not known in advance, applying this model can be difficult or impossible.

It can be seen that all models are designed to be used in specific scenarios. Our goal is to find radio propagation models which are accurate in path loss prediction, easily tunable and applicable in a disaster scenario, where it is impossible to know the site information in advance.

Thus, we have chosen the most appropriate models to be evaluated according to our mixed outdoor-indoor scenario - SUI model, Hata model, COST-231 Hata model, free space model, log-distance model, ITU indoor and outdoor models. The purpose of our experiment was to collect RSS data and determine whether the chosen signal propagation models fit experimental data or not. For that, the path loss exponent and the intercept (the sum of the transmitted power and wall attenuation factor) was determined. Next, the evaluation and comparison between models is presented.

3 Evaluation Scenario

For the evaluation, we have chosen the following scenario. The experiment was performed at Leonardo da Vinci building in the campus of TU Ilmenau. We have used seven different mobile phones as receivers placed inside of the building and one MAV equipped with a GSM base station as a transmitter placed outside the building. The MAV with the mounted GSM base station is shown in Fig. 1. In such a way, we achieve a mixed outdoor-indoor scenario. The building plan and the distribution of the nodes is seen in Fig. 2. Weather and experiment setup are given in Table 2. The GSM base station was implemented using Software Defined Radio (SDR) with omni-directional antennas and the open-source software – OpenBTS [20]. The goal of our experiment was to collect RSSI measurements in

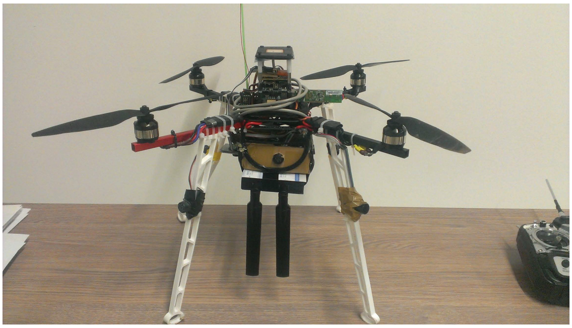

Fig. 1. The quadcopter with GSM BS on board.

order to develop an empirical GSM model for outdoor-indoor scenario. We have used collected RSSI from all seven phones to develop our model. We did not analyze data separately for every phone, it was averaged among all used mobile phones. In such a way we wanted to avoid dependencies on the specific model, antenna or transceiver unit of the mobile phone. Outdoor measurements were taken both in front and rear of the building, by placing MAV at the distances of $5, 10, 15, 20, 25, 30, 35\,\text{m}$ in the front and $5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55\,\text{m}$ in the rear. For every new placement of the MAV, 120 measurements have been taken for each mobile phone. We have also performed a series of indoor measurements, as some models require a reference measurement at the distance $d = 1\,\text{m}$.

Table 2. Weather and experiment setup.

Parameter	Name/Value
Air temperature	-2^o
Humidity	83 %
Speed of wind	3 km/h
Air pressure	1027 mbar
Building size	$20 \times 30\,\text{m}^2$
Uplink frequency	1710.2 MHz
Downlink frequency	1805.2 MHz
Number of nodes	7
Measured parameter	RSSI

As the log-distance model is a very general model which can be applied indoors and outdoors, as well as extended with a wall attenuation factor, it was decided to adapt this model to our scenario. For the empirical model development, we had to determine a path loss exponent γ and an intercept I.

Our goal was to develop an easily tunable model, for that we avoid having too many parameters, like wall attenuation factor, floor penetration loss factor, etc.

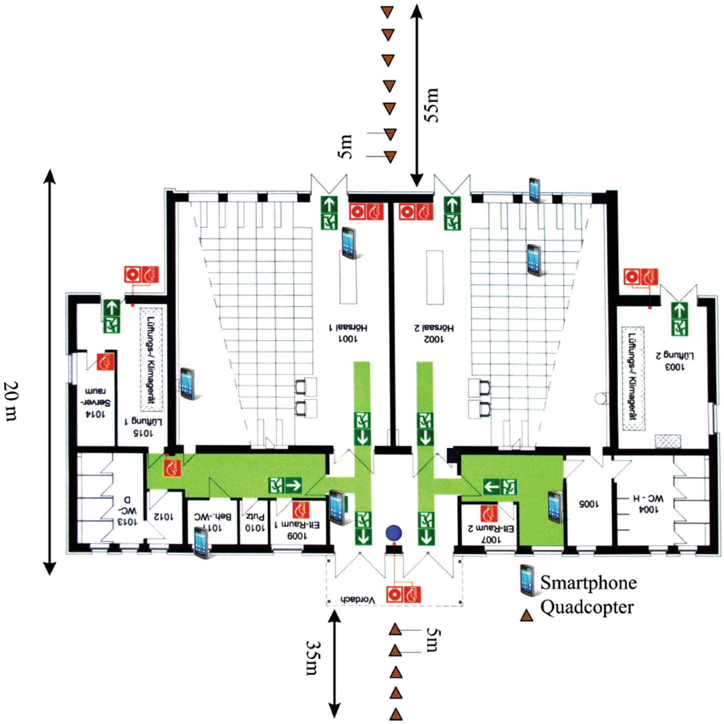

Fig. 2. Floor plan of Leonardo da Vinci building at technical university of Ilmenau. Mobile phones were located inside the building. MAV was placed outside the building in front and rear. Positions are marked accordingly.

Table 3. Propagation parameters for the evaluation.

Parameters	Values
Frequency	1805.2 MHz
Distance d_0	1 m
Receiving antenna height (smartphone)	0.5 m
Transmitting antenna height (MAV)	1.5 m
Path loss exponent γ	[1, 5]
Intercept	[0, 100] dBm
Floor penetration loss factor $L_f(n)$	0

As opposite to the existing models, we combine all these factors to one parameter and call it intercept. We will call it adapted log-distance model and express it as:

$$L_{adapted} = 10\gamma \log_{10} d + I \tag{1}$$

Algorithm 1. Adaptation of signal propagation models using RMSE

$D \leftarrow$ array of distances
$P_r \leftarrow$ array of experimentally obtained received signal strengths
$P_{rmodel} \leftarrow$ array of calculated received signal strengths
$error_{min} \leftarrow \infty$
for $\gamma \leftarrow 1.0, 5.0$ step 0.001 **do**
  for all D **do**
    $error, intercept \leftarrow calculateRMSE(\gamma, D, P_r, P_{rmodel})$
    if $error <= error_{min}$ **then**
      $error_{min} = error$
      $\gamma_{best} = \gamma$
      $intercept_{best} = intercept$
    end if
  end for
end for
return $error_{min}, \gamma_{best}, intercept_{best}$

Propagation parameters used for the evaluation of the results are given in Table 3. We have used these parameters to find the signal propagation model which has the closest fit to our experimental data. The brute force method was used to iterate over all possible values for the path loss exponent (from 1 to 5) and the intercept (from 0 to 100 dBm), as it can be seen in Algorithm 3. For every combination of γ and I, RMSE has been calculated as a measure of similarity to our empirical data and can be expressed as:

$$RMSE = \sqrt{\frac{\sum_{j=1}^{N}(L_{model_j} - L_{measured_j})^2}{N}} \tag{2}$$

where L_{model_j} is the value of chosen model in dBm, $L_{measured_j}$ is the measured value in dBm and N is the amount of measurements.

The next chapter will present our evaluation results for the chosen models.

4 Evaluation Results

The path loss in dBm with respect to the distance between the MAV and mobile phones was measured. In Fig. 3 the average signal strength values using both indoor and outdoor measurements are plotted. As predicted, the measured data follows logarithmic distribution.

Furthermore in Fig. 3 five curves are plotted: the adapted log-distance model, COST-231 Hata model, ITU indoor and outdoor models, as well as the log-distance model. These models represent the best fit according to the RMSE. As can be seen from figure, all five models are located quite close to developed empirical model presented by the adapted log-distance model. To identify the best fit, RMSE values should be analyzed.

As depicted in Fig. 4, the adapted log-distance model has the lowest RMSE and represents the best fit to our measured data. It outperforms its opponents

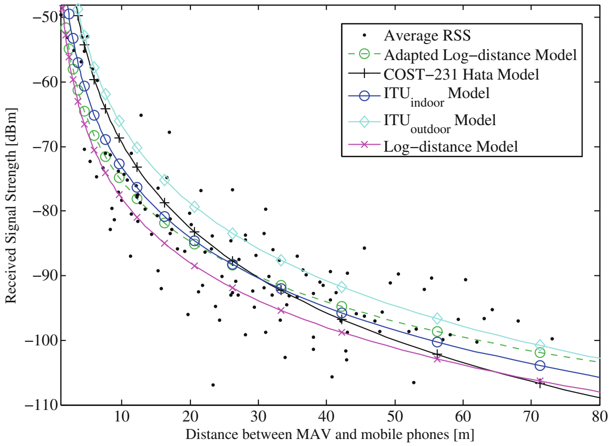

Fig. 3. Path loss in dBm vs. distance in a mixed outdoor-indoor scenario.

with the RMSE value of 6.05 m. Taking into account all measurements, the adapted log-distance model presented $\gamma = 3.1$ and intercept equal to 44.14 dBm. Values of γ and intercept for all five models are given in Table 4. Moreover, ITU indoor model has the second best fit to the measured data with the RMSE value of 6.3 m. Also, the third best fit was presented by the log-distance model. It is worth noticing that COST-231 Hata and ITU outdoor models have γ values of 4.4 and 4.0 accordingly, which is not realistic for our scenario. The chosen building for the experiment was distanced from the other buildings, there was low traffic and as a consequence expected path loss value should be in the range of 3–3.5. Furthermore, it was stated in [16] that values of γ from 4 to 6 are only typical for indoor areas.

As a result, we have developed an empirical GSM model which is suited for a scenario where a transmitter is located outside the building and mobile phones are placed inside. Using Eq. 1 resulting adapted log-distance model can be written as:

$$L_{adapted} = 10 \cdot 3.1 \log_{10} d + 44.1 \tag{3}$$

Table 4. Path loss exponent and intercept values for the chosen models.

Model	γ	Intercept, dBm
Adapted log-distance	3.1	44.1
COST-231 Hata	4.4	25.6
ITU_{indoor}	3.6	37.1
$ITU_{outdoor}$	4.0	26.7
Log-distance	3.3	44.8

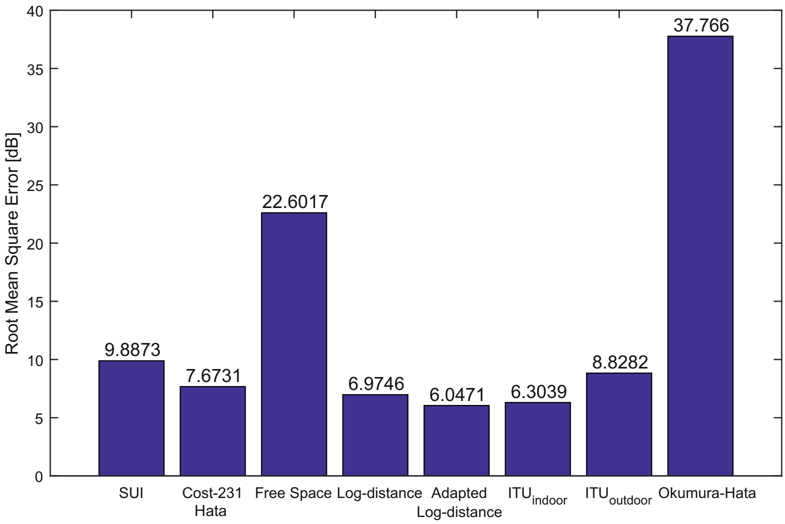

Fig. 4. Evaluation of chosen models in terms of root mean square error.

The transmitter and the receiver can be separated by up to four walls. Nevertheless we have collected our measurements only in one site, this model could also be used in other similar outdoor-indoor scenarios. This should be validated and will be a part of our future work.

5 Conclusion

In this paper a comprehensive study and analysis of wireless propagation models were made. Our goal was to find a model which can accurately map distance to the RSS as this will signficantly increase a localization accuracy. Analytical analysis has shown that SUI model, Hata model, COST-231 Hata model, free space model, log-distance model, ITU indoor and outdoor models could be the best candidates for prediction of path loss in a mixed outdoor-indoor scenario. In order to validate chosen models a measurement campaign was performed.

Evaluation results were the following:

- Adapted log-distance model presents the best fit to our data with RMSE value of 6.05 m with path loss exponent being $\gamma = 3.1$ and intercept = 44.1 dBm.
- The second best fit was presented by ITU indoor model with RMSE value being 6.3 m. Altered parameters for this model were $\gamma = 3.6$ and intercept = 37.1 dBm.
- Worst fit was presented by COST-231 Hata and ITU outdoor models which had γ values of 4.4 and 4.0 accordingly, which is not realistic for our scenario.

As a result we can state that developed log-distance model can be used in any scenario where mobile phones are located inside the building and flying GSM base station is placed outside. However, this should be validated and will be a part of our future work.

References

1. Ezzine, R., Braham, R., Al-Fuqaha, A., Belghith, A.: A new generic model for signal propagation in Wi-Fi and WiMAX environments. IEEE (2008)
2. Artemenko, O., Rubina, A., Simon, T., Mitschele-Thiel, A.: Evaluation of different static trajectories for the localization of users in a mixed indoor-outdoor scenario using a real unmanned aerial vehicle. In: 7th International Conference on Ad Hoc Networks (ADHOCNETS 2015), San Remo, Italy, September 2015
3. Artemenko, O., Rubina, A., Golokolenko, O., Simon, T., Rämisch, J., Mitschele-Thiel, A.: Validation and evaluation of the chosen path planning algorithm for localization of nodes using an unmanned aerial vehicle in disaster scenarios. In: 6th International Conference on Ad Hoc Networks (ADHOCNETS 2014), Rhodes, Greece, Best Paper Award, August 2014
4. Otsason, V., Varshavsky, A., LaMarca, A., de Lara, E.: Accurate GSM indoor localization. In: 7th International Conference, UbiComp 2005: Ubiquitous Computing 2005, Proceedings, Tokyo, Japan, 11–14 September 2005, pp. 141–158 (2005)
5. Goldsmith, A.: Wireless Communications. Stanford University, California (2004)
6. IEEE: Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications. IEEE (2012)
7. Rao, G.S.: Cellular Mobile Communication. Pearson, London (2013)
8. Hata, M.: Empirical formula for propagation loss in land mobile radio services. IEEE Transactions on Vehicular Technology **29**(3), 317–325 (1980)
9. Damosso, E., Correia, L.M.: COST action 231: digital mobile radio towards future generation systems: final report, European commission (1999)
10. Walfisch, J., Bertoni, H.L.: A theoretical model of UHF propagation in urban environments. IEEE Transactions on Antennas and Propagation **36**(12), 1788–1796 (1988)
11. Löw, K.: Comparison of urban propagation models with CW-measurements. In: IEEE 42nd Vehicular Technology Conference, pp. 936–942. IEEE (1992)
12. Bruning, S., Zapotoczky, J., Ibach, P., Stantchev, V.: Cooperative positioning with magicmap. In: 4th Workshop on Positioning, Navigation and Communication, 2007. WPNC 2007, 17–22 March 2007
13. Rappaport, T.: Wireless Communications: Principles and Practice. Prentice Hall PTR, Upper Saddle River (2001)
14. Erceg, V., Hari, K., Smith, M., Baum, D.S., Sheikh, K., Tappenden, C., Costa, J., Bushue, C., Sarajedini, A., Schwartz, R., et al.: Channel models for fixed wireless applications (2001)
15. Faria, D.B.: Modeling signal attenuation in IEEE 802.11 wireless LANs, vol. 1. Technical report TR-Kpp, 06-0118, Kiwi Project, Stanford University, January 2006
16. Abhayawardhana, V., Wassell, I., Crosby, D., Sellars, M., Brown, M.: Comparison of empirical propagation path loss models for fixed wireless access systems. In: 2005 IEEE 61st Vehicular Technology Conference, VTC 2005-Spring, vol. 1, pp. 73–77. IEEE (2005)

17. Union, I.T.: P.1238: Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz (2015)
18. Union, I.T.: P.1411: propagation data and prediction methods for the planning of short-range outdoor radiocommunication systems and radio local area networks in the frequency range 300 MHz to 100 GHz (2015)
19. Leppänen, R., Lähteenmäki, J., Tallqvist, S.: Radiowave propagation at 900 and 1800 MHz bands in wooded environments. IEEE Transactions on Antennas and Propagation **92**, 112 (1992)
20. Loula, A.: OpenBTS installation and configuration guide (2009). http://openbts.org/documentation/