Joint Antenna and Propagation Model Parameter Estimation using RSS measurements

Parinaz Kasebzadeh, Carsten Fritsche, Emre Özkan, Fredrik Gunnarsson[†], Fredrik Gustafsson
Department of Electrical Engineering, Linköping University, Linköping, Sweden
Email: parinaz.kasebzadeh@liu.se, {carsten, emre, fredrik}@isy.liu.se
[†] Ericsson Research, Linköping, Sweden, Email: fredrik.gunnarsson@ericsson.com

Abstract—**In this paper, a semi-parametric model for RSS measurements is introduced that can be used to predict coverage in cellular radio networks. The model is composed of an empirical log-distance model and a deterministic antenna gain model that accounts for possible non-uniform base station antenna radiation. A least-squares estimator is proposed to jointly estimate the path loss and antenna gain model parameters. Simulation as well as experimental results verify the efficacy of this approach. The method can provide improved accuracy compared to conventional path loss based estimation methods.**

I. INTRODUCTION

The high pace of development of geographical positioning methods along with tracking mobile users might be routed to various sources. Navigation, people and assets tracking, location based security and coordination of emergency and maintenance responses to accidents, interruptions of essential services, mapping the location of disaster victims, cellular system design and management are examples of different applications and services which rely on the accurate position estimation [1].

The first enabling Global Navigation Satellite System (GNSS)-based positioning methods such as those based on Global Positioning System (GPS) are still in use in many applications. Briefly speaking, those methods are based on signals transmitted from satellites and as mentioned are a primary source of location estimations for many applications. However, the negative-affecting factors impose the necessity of evolution of conventional approaches. For example, outdoor environments such as "urban canions", bad weather conditions resulting in poor signals, and indoor environments where the signal is totally non-accessible, other alternatives must be applied. Assisting GNSS signals with other wireless networks such as the Third Generation Partnership Project (3GPP), Long Term Evolution (LTE) or IEEE 802.11, that is studied widely in the literature (for different applications, see [2]–[4]), is one solution to increase both availability of service and the accuracy of estimation. On the other hand, in indoor environments, relying on available Wireless LAN (WLAN) infrastructures for position estimation purposes is investigated for a long term where, [5]–[11] can be seen as examples.

Cellular radio network positioning can be seen as an alternative to Assisted GPS (A-GPS) systems mentioned above, when the latter is unavailable. Example use cases include emergency call positioning. Furthermore, from a radio network management perspective, the positioned radio measurement enables an operator to identify where issues such as poor coverage or excessive interference are located. Commonly, one distinguish between network-centric and mobile-centric solutions. In the former, a network entity estimates the position of a terminal, possibly based on measurements reported by the terminal. Moreover, in the latter, the terminal is provided with assistance data to enable it to estimate its position. The position estimate may also be based on a measurement snapshot, or a time series of measurements. The measurements are typically related to time of arrival (TOA), received signal strength (RSS) and angle of arrival (AoA) of transmitted reference signals, or combinations thereof [12].

RSS measurements are typically reported from the terminal to the base station for other reasons than positioning, such as handover from a serving cell to a target cell, radio resource management in general, or to assess the properties of the radio conditions in a cell as part of network management. Therefore, they can be seen as readily available. In a positioning context, RSS measurements are used for ranging and fingerprinting [12]. Recently, it has also been shown how RSS measurements together with information about base station antenna properties, can be used to estimate the angle of arrival [13]. Also, knowledge about the serving sector cell together with information about the sectorized antenna, yields a crude estimate of the angle of arrival for the terminal. The performance of positioning based on such bearing estimates is assessed in [14], and in [12]. The latter also address the positioning performance given RSS measurements used for ranging, given a parametric radio propagation model.

Two main approaches that are widely studied in the literature that use RSS measurements for positioning purposes, are channel modeling [15], [16] and fingerprinting [17], [18]. Both of these two however, suffer from lack of considering simultaneous effects of channel and antenna parameters on RSS measurements they use for positioning algorithms. Moreover, the change of channel and antenna parameters based on the instantaneous propagation condition is also neglected. If detailed propagation model calibration is ruled out, the applicability of the RSS measurements for ranging is subject to significant uncertainty. Such uncertainty can be considered in the positioning algorithm, but still with fairly inaccurate positioning performance as a result [19].

An alternative is to take advantage of the recent development of smartphones, capable of logging accurate GPS positions and RSS measurements. Thereby, it is possible to retrieve such trajectories at a calibration entity and use for model parameter calibrations. Traditionally, close range measurements have been used to measure the antenna gain in detail, while avoiding significant propagation effects. Moreover, positioned RSS measurements have been modified in consideration of the antenna model to determine corresponding RSS measurements from an isotropic antenna, which in turn has been used to estimate the parameters of the propagation model.

In this paper, we present a method to jointly estimate both the antenna and propagation model parameters using positioned RSS measurements. The rest of the paper is organized as follows: In Section II a semi-empirical model for RSS measurement is presented. Section III addresses requirements for joint propagation model and antenna parameter estimation representation. Section IV evaluates performance of the proposed model using simulations followed by verifications applied on real-field data provided in Section V. Finally, Section VI concludes the work.

II. RSS MEASUREMENT MODEL

The RSS measurement y can be expressed by the following general model

$$y = h(x) + e, \tag{1}$$

where $h(x)$ is a propagation model (sometimes also called radio channel) that accounts for propagation effects, such as attenuation, diffraction, or reflection, that the electromagnetic wave is affected by, when traveling between the Mobile Station (MS) and the Base Station (BS). Here, x denotes a (vector) variable providing relative position dependent information of the MS and the BS and/or the environment, and e represents a statistical noise term (here assumed to be additive) that accounts for effects that cannot be captured by the propagation model.

The propagation models can be broadly categorized into three types: deterministic, empirical, and semi-empirical models [1]. The deterministic models are based on techniques such as ray tracing or ray launching that require accurate knowledge of the environment such as high resolution building data. These models are very accurate, but also the most complex ones. Empirical models use heuristic equations that have been derived from extensive measurement campaigns. These models are very simple, but less accurate than their deterministic counterparts. Among the most popular empirical models are the Okumura-Hata and COST 231 models [1], [20], [21]. Semi-empirical models are composed of both deterministic and empirical models and provide a good compromise between accuracy and complexity.

In the following, we introduce a semi-empirical propagation model for the RSS measurement. It combines an empirical distance-dependent propagation loss (or path loss) model $L(x)$ with a deterministic model $G_{\text{ant}}(x)$ representing the possible non-uniform radiation of the BS antenna with respect to the MS position (antenna gain model). We further make the common assumption that the RSS measurement is time-averaged, such that temporal effects resulting from small-scale fading can be neglected. Hence, the proposed semi-empirical model for the RSS measurement in logarithmic scale (dBm) can be written as

$$y = P_{\text{T}} - \{L(x) - G_{\text{ant}}(x)\} + e, \tag{2}$$

where $x \triangleq [d, \phi, \psi]^T$ is the vector holding the relative position information of the MS with respect to the BS antenna, P_{T} is the BS transmit power in dBm, and e is a statistical term which accounts for the errors resulting from quantization, slow fading and other effects that are not captured by the propagation model. The error term e is modeled with a zero-mean Gaussian distribution with variance σ^2.

A. Path Loss Model

A path loss (PL) model presents signal attenuation in space. In this work, the log-distance model is used as it forms the basis of most models available in the literature [22], [5]. The log-distance model is given by

$$L(d) = A + 10B \log_{10}\left(\frac{d}{d_0}\right), \tag{3}$$

where A is the reference path loss, B is the path loss exponent, d is the Euclidean distance between the MS and BS, and d_0 represents the distance at which the reference path loss A is determined. The value of d_0 generally depends on the cell size, and values that can be typically found are $100\,\text{m}$ or $1\,\text{km}$.

B. Antenna Gain Model

Base station antenna modeling mainly concerns crude models that capture the far-field (at some distance from the antenna) gain in various directions. Models, that have become popular in recent years are separated into one horizontal plane model $G_{\text{h}}(\phi)$ and one vertical plane model $G_{\text{v}}(\psi)$, and the combined antenna gain is merely the two model contributions added together in logarithmic scale according to

$$G_{\text{ant}}(\phi, \psi) = G_{\text{h}}(\phi) + G_{\text{v}}(\psi). \tag{4}$$

Simplified models neglect the vertical component and model only the horizontal antenna gain. In this work, we consider the antenna gain model proposed in [23] that is also adopted for the radio network evaluations in 3GPP. The horizontal gain model is given by

$$G_{\text{h}}\left(\phi\right) = G_{\text{max}} - \min\left(12\left(\frac{\phi - \phi_0}{\phi_{\text{h}}}\right)^2, G_{\text{h,min}}\right), \tag{5}$$

where G_{max} denotes the maximum antenna gain in dBi, $-180^\circ < \phi \leq 180^\circ$ is the antenna azimuth angle defined in the xy-plane, counted counter-clockwise from the positive x-axis, ϕ_{h} is the antenna's horizontal bandwidth in degree, which represents the bandwidth at which the antenna gain is half of the maximum gain (also known as half-power beamwidth), ϕ_0 is the antenna angle in degree pointing into the direction of maximum gain (antenna boresight angle), and $G_{\text{h,min}}$ denotes the front-to-back ratio measured in dB, given the relative difference between antenna beam direction gain $G_{\text{h}}\left(\phi_0\right) = G_{\text{max}}$ and the back lobe gain $G_{\text{h}}\left(\phi_0 + 180^\circ\right) = G_{\text{max}} - G_{\text{h,min}}$. The vertical antenna gain is modeled with

$$G_{\text{v}}(\psi) = \max\left(-12\left(\frac{\psi - \psi_{\text{etilt}}}{\psi_{\text{v}}}\right)^2, G_{\text{v,min}}\right), \tag{6}$$

where $-90^\circ < \psi \leq 90^\circ$ is the negative antenna elevation angle relative to the horizontal plane, i.e. $\psi = 90^\circ$ is downwards, $\psi = 0^\circ$ is along the horizontal plane, and $\psi = -90^\circ$ is upwards. The angle ψ_{etilt} given in degree is the electrical antenna downtilt that models the angle downwards from the horizontal plane at which the antenna is electrically directed, ψ_{v} is the antenna's half-power beamwidth in the vertical direction, and $G_{\text{v,min}}$ is the side lobe level in dB of the vertical pattern that represents the side lobe gain level in relation to the antenna vertical beam direction gain. As an example, Figure 1 illustrates the horizontal antenna gain model (5), together with real data from an antenna, see [23] for an additional example including the vertical antenna gain model.

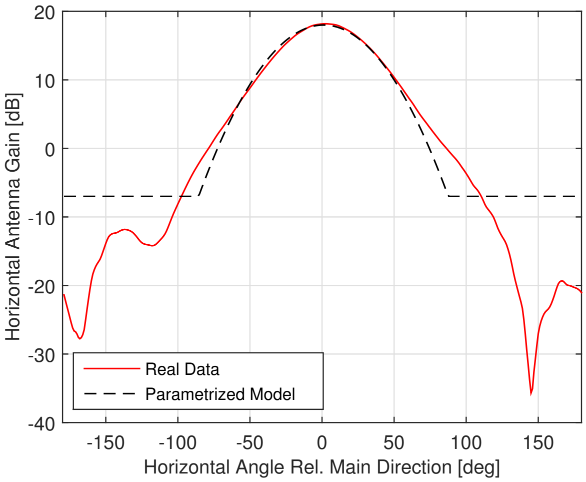

Fig. 1: Illustration of horizontal antenna gain pattern

III. JOINT PATH LOSS AND ANTENNA PARAMETER ESTIMATION

The joint contribution of the attenuation due to path loss and the antenna gain enter the measurement equation additively. Hence identification of some parameters is not possible due to unobservability. For instance, it is not possible to estimate the reference path loss A and the maximum antenna gain G_{max} separately. Another issue with the joint parameters estimation is that the antenna gain is modeled different inside and outside the main lobe using $\min(,)$ and $\max(,)$ functions which results in non-linear equations. Under the assumption that the main lobe components are dominant, the contribution of the antenna gain simplifies to

$$\tilde{G}_{\text{ant}}(\phi, \psi) = G_{\text{max}} - 12\left(\frac{\phi - \phi_0}{\phi_{\text{h}}}\right)^2 - 12\left(\frac{\psi - \psi_{\text{etilt}}}{\psi_{\text{v}}}\right)^2. \tag{7}$$

With this simplification, the maximum likelihood estimate of the parameters becomes tractable, and can be found according to

$$\hat{\theta}^{\text{ML}} = \arg\max_{\theta \in \Theta} p(Y|\theta), \tag{8}$$

where Y is an independent and identically distributed (i.i.d.) sequence of m RSS measurements and θ are the unknowns. Under the Gaussian noise assumption the maximum likelihood solution is equivalent to the least squares estimator. The RSS measurement becomes linear in the following unknown parameters $\theta = [A, B, \phi_{\text{h}}^{-2}, \psi_{\text{v}}^{-2}]^T$, where it has been assumed that the antenna main direction ϕ_0, the electrical downtilt ψ_{etilt}, the transmission power P_T and the maximum antenna gain G_m all are known. The least squares estimate is given as

$$\hat{\theta}^{\text{LS}} = \hat{\theta}^{\text{ML}} = (H^T H)^{-1} H^T Z, \tag{9}$$

where

$$H \triangleq \begin{bmatrix} 1 & 10\log_{10}(\frac{d_1}{d_0}) & 12(\phi_1 - \phi_0)^2 & 12(\psi_1 - \psi_{\text{etilt}})^2 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & 10\log_{10}(\frac{d_m}{d_0}) & 12(\phi_m - \phi_0)^2 & 12(\psi_m - \psi_{\text{etilt}})^2 \end{bmatrix}, \tag{10}$$

and

$$Z \triangleq \begin{bmatrix} P_{\text{T}} + G_{\text{max}} - y_1 \\ \vdots \\ P_{\text{T}} + G_{\text{max}} - y_m \end{bmatrix}. \tag{11}$$

An unbiased estimate of the noise variance $\hat{\sigma}^2$ is given by

$$\hat{\sigma}^2 = \frac{1}{m-1}\sum_{i=1}^{m}(\hat{z}_i - z_i)^2, \tag{12}$$

where $\hat{z}_i$'s are found by plugging in the least squares solution into $\hat{Z} = H\hat{\theta}^{\text{LS}}$. As already stated earlier, the BS transmit power P_{T} and maximum antenna gain G_{max} can not be estimated separately from the path loss parameter A. Therefore, it is reasonable to assume them a priori known, or to approximate them using nominal values taken from antenna specification documents, or by lumping these parameters together forming the new (unknown) parameter $\tilde{A} = P_{\text{T}} - A + G_{\text{max}}$, that is to be estimated instead.

For the main lobe assumption to hold, the horizontal and vertical angles needs to be close to the antenna main beam direction. This implies the following boundary conditions to be satisfied:

$$|\phi - \phi_0| < \phi_{\text{h}}\sqrt{\frac{G_{\text{h,min}}}{12}}, \tag{13a}$$

$$|\psi - \psi_{\text{etilt}}| < \psi_{\text{v}}\sqrt{\frac{-G_{\text{v,min}}}{12}}. \tag{13b}$$

Clearly, the boundary conditions depend on the unknown parameters ϕ_{h} and ϕ_{v}, making it difficult to motivate considering only those RSS measurements in the estimation process that fulfill the above requirements. However, it is always possible to use smaller values for the parameters in (13) deviating from the nominal values that can be typically found in antenna specification documents, implying a smaller main lobe area from which RSS measurements can be used in the estimation process. However, these parameters should be carefully selected in order to avoid deteriorating the estimation results, for instance by assuming a too small main lobe area.

IV. SIMULATED DATA EXPERIMENTS

In this section, the performance of the algorithm proposed in the previous section is tested on simulated data. The RSS measurements are generated from (2) using the parametrized antenna gain model, see (5) and (6). In Table I, the path loss and antenna gain model parameters are listed that have been used in the simulations. The antenna parameters correspond to typical values that can be found in antenna specifications. The path loss exponent B is typically between 2 (free-space propagation) and 4 (dense urban environment) and has been chosen slightly above the free-space propagation, in order to better reflect outdoor BS deployments in rural areas. For the antenna parameters given in Table I, it is possible to derive the boundary conditions (13), where RSS measurements shall be collected in order to not violate the simplified antenna gain model assumption (7).

TABLE I: List of path loss and antenna model parameters

Parameter	Description	Value
P_{T}	BS transmit power	32 dBm
A	Reference path loss	100 dB
B	Path loss exponent	2.3 dB
d_0	Reference Distance	1000 m
σ	Error standard deviation	4 dB
G_{max}	Maximum gain	18 dBi
ϕ_{h}	Horizontal beamwidth	65°
ϕ_0	Boresight angle	0°
$G_{\mathrm{h,min}}$	Front-to-back ratio	30 dB
ψ_{etilt}	Vertical downtilt	9°
ψ_{v}	Vertical beamwidth	7°
$G_{\mathrm{v,min}}$	Side lobe level	-18 dB
h_{BS}	BS height	30 m

It is easy to show that for an antenna with the parameters given in Table I, the requirements for the main lobe area are given by $-103° \leq \phi \leq 103°$ and $0.4° \leq \psi \leq 17.6°$, respectively. The azimuth requirement corresponds to more than the entire 120° sector the antenna normally covers (Note, that in cellular radio networks each cell site is normally equipped with three antennas each covering a 120° sector). With a relative antenna height of 30 m, this means that the elevation requirements are valid for distances from the BS between $30\,\mathrm{m}/\tan(17.6°) \approx 95$ m and $30\,\mathrm{m}/\tan(0.4°) \approx 4030$ m. On the other hand, if we assume smaller values for the half-power beamwidth, e.g. $\phi_{\mathrm{h}} = 60°$ and $\phi_{\mathrm{v}} = 6°$, the main lobe area from which RSS measurements could be used in the estimation process, would shrink to $-95° \leq \phi \leq 95°$ and $1.7° \leq \psi \leq 16.4°$, yielding distances from the BS between 102 m and 1040 m, which is still acceptable.

Based on the above results, i.i.d. RSS measurements are generated by distributing MS positions uniformly within the main lobe area. Here, we distinguish between the true boundary conditions and the approximate boundary conditions that have been introduced above. The estimation results are shown in Table II and III, respectively.

TABLE II: Estimation results for true boundary conditions

Parameter	A [dB]	B [dB]	ϕ_{h} [°]	ψ_{v} [°]	σ [dB]
True	**100**	**2.3**	**65**	**7**	**4**
Est. ($m = 1e3$)	99.46	2.23	64.88	6.83	4.07
Est. ($m = 2e3$)	99.86	2.27	64.92	6.93	3.96
Est. ($m = 5e4$)	100.37	2.33	64.99	7.11	4.03

It can be observed that the estimation results improve as the number of RSS measurements m used in the least-squares solution is increased. It can be also seen that there is essentially no difference whether the true boundary conditions or the approximate boundary conditions are used to select the RSS measurements for the parameter estimation process.

TABLE III: Estimation results for approximate boundary conditions

Parameter	A [dB]	B [dB]	ϕ_{h} [°]	ψ_{v} [°]	σ [dB]
True	**100**	**2.3**	**65**	**7**	**4**
Est. ($m = 1e3$)	100.25	2.35	64.83	7.09	3.97
Est. ($m = 2e3$)	99.87	2.36	64.99	6.91	4.06
Est. ($m = 5e4$)	100.05	2.32	64.98	7.02	4.01

As an example, the estimation results of the path loss parameters are shown in Figure 2 for the method using the approximate boundary conditions. It can be observed that the estimated path loss slope is in good agreement with the true slope. Note, that the RSS measurements still contain the contribution from the antenna gain and thus the true and estimated slope do not follow the trend of the RSS values. For comparison purposes, we have also included the path loss slope when the estimator is only estimating the path loss parameters, i.e. $G_{\mathrm{ant}} = 0$ in the estimator model. In this case, we have a model mismatch and the path loss slope follows the trend of the RSS measurements, as expected.

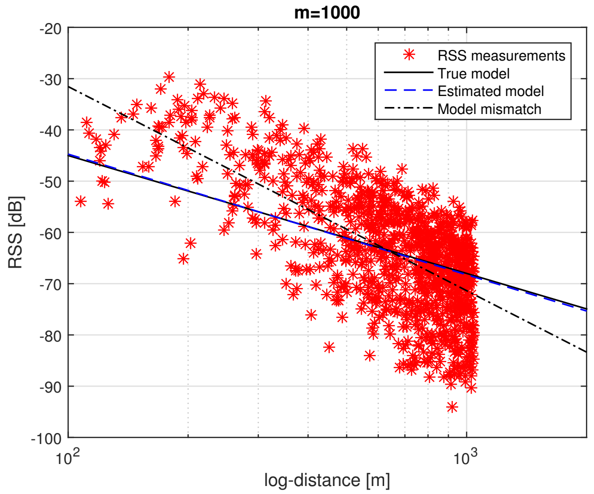

Fig. 2: Path loss estimation results for simulated data using approximate boundary conditions and $m = 1000$.

For the model mismatch case, we also included the estimation results for different number of RSS measurements taken from the approximate boundary conditions, which are shown in Table IV. It is now also observed that the error standard deviation is much larger, which is due to the compensation of unmodeled antenna gain variations. The benefits of adopting a joint antenna and propagation model in comparison to only a propagation model is this evident.

TABLE IV: Estimation results for model mismatch and approximate boundary conditions

Parameter	A [dB]	B [dB]	σ [dB]
True	**100**	**2.3**	**4**
Est. ($m = 1e3$)	103.37	3.98	8.40
Est. ($m = 2e3$)	103.21	3.84	8.55
Est. ($m = 5e4$)	103.39	4.01	8.68

V. REAL DATA EXPERIMENTS

The proposed joint antenna and propagation model described in the previous section is also verified with real-field measurements. The measurements are collected in a rural/suburban area, with an Android app for logging A-GPS and RSS [24]. The smartphone was configured to camp on a 3GPP LTE/E-UTRAN network, which means that the logging reflects Reference Signal Received Power (RSRP).

In order to identify the parameters accurately, a direct LOS between the MS and BS is preferable. One base station is chosen in an area where buildings and similar structures that can obscure a direct LOS are rather sparse. The selected base station feeds antennas mounted on a mast which is 30 m high. The BS serves three cells each covering 120 degrees, and one of the cells (with an antenna boresight direction $\phi_0 = -30°$) is used for evaluation purposes. The antenna associated to the cell has a halfpower beamwidth of 60 degrees. However, not that this is the beamwidth observed near the antenna. Signal scattering will spread the signals, effectively creating an antenna that is perceived to be wider by a distant observer. It is therefore expected that the estimated horizontal halfpower beamwidth is slightly wider than the nominal beamwidth of 60 degrees, and the vertical halfpower beamwidth wider than the nominal bandwidth of 7 degrees.

The measurements are collected over several trajectories around the site as depicted in Figure 3. In the same figure, the RSS values are also presented with colors.

Measurements were selected that are assumed to be in the horizontal main lobe of the antenna, with boundary conditions $|\phi - \phi_0| \leq 50°$. The region is quite flat and the trajectories are not in close vicinity of the antenna. Therefore there is not much variety in vertical angles. The contribution from the vertical antenna gain is expected to be smaller than 0.1dB under the assumption of nominal value of the parameters. Hence its effect is neglected for the scenario, and the vertical antenna gain component is omitted from the joint model. The estimated parameters under these assumptions are given in Table V. As expected, the estimated effective horizontal antenna halfpower beamwidth ϕ_h is wider than the nominal beamwidth due to scattering. Furthermore, the residual standard deviation of 7 dB is in the expected range of 6-10 dB [12].

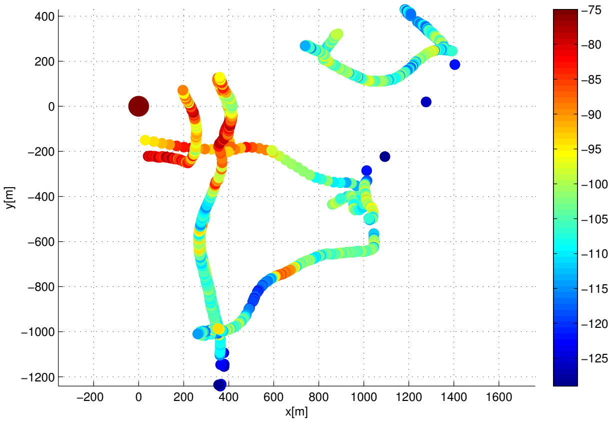

Fig. 3: The RSS values collected along different trajectories around the antenna. Antenna location is shown by the big circle

TABLE V: Estimation results for real data experiments using only horizontal antenna gain pattern

Parameter	A [dB]	B [dB]	ϕ_h [°]	σ [dB]
Est. ($m = 1252$)	152.6	2.9675	79.5823	7.0265

Figure 4 illustrates the fit of the propagation model component, which indicates a good fit. These brief evaluations indicate the relevance and benefits of joint antenna and propagation model parameter estimation.

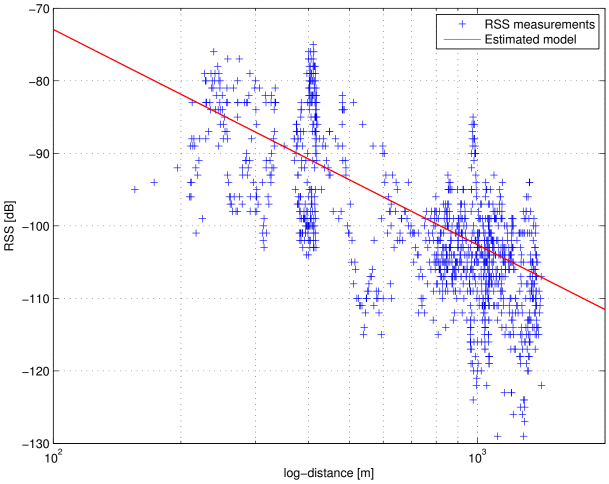

Fig. 4: RSS measurements together with estimated path loss model

VI. CONCLUSION

In this paper we propose an algorithm for joint antenna and propagation model parameter estimation. The associated parameter estimation problem can be formulated as a least squares problem, which enables efficient estimation of the model parameters. The problem is considered tractable given measurement trajectories with positioned RSS measurements within the main lobe of the antenna. The proposed method has been evaluated using both simulated and real RSS measurement with promising results. The results also indicate that the joint antenna and propagation model provide significantly better accuracy compared to a propagation model alone.

VII. ACKNOWLEDGMENT

This work is funded by the European Union FP7 Marie Curie training programme on Tracking in Complex Sensor Systems (TRAX) with grant number 607400.

REFERENCES

[1] J. J. Caffery, *Wireless Location in CDMA Cellular Radio Systems*. Norwell, MA, USA: Kluwer Academic Publishers, 1999.

[2] R. S. Nerem and K. M. Larson, "Global positioning system, theory and practice, " *Eos, Transactions American Geophysical Union*, vol. 82, no. 33, pp. 361-365, August 2001.

[3] P. A. Zandbergen, "Accuracy of iphone locations: A comparison of assisted GPS, WiFi and cellular positioning," *Transactions in GIS*, vol. 13, pp. 5-25, June 2009.

[4] A. J. Coutts and R. Duffield, "Validity and reliability of GPS devices for measuring movement demands of team sports," *Journal of Science and Medicine in Sport*, vol. 13, no. 1, pp. 133-135, January 2010.

[5] P. Kasebzadeh, G.-S. Granados, and E. Lohan, "Indoor localization via WLAN path-loss models and Dempster-Shafer combining," in *Localization and GNSS (ICL-GNSS), International Conference on*, pp. 1-6, June 2014.

[6] C. Feng, W. Au, S. Valaee, and Z. Tan, "Received-Signal-Strength-Based indoor positioning using compressive sensing," *Mobile Computing, IEEE Transactions on*, vol. 11, no. 12, pp. 1983–1993, December 2012.

[7] N. Chang, R. Rashidzadeh, and M. Ahmadi, "Robust indoor positioning using differential Wi-Fi access points," *Consumer Electronics, IEEE Transactions on*, vol. 56, no. 3, pp. 1860–1867, August 2010.

[8] E. Martin, O. Vinyals, G. Friedland, and R. Bajcsy, "Precise indoor localization using smart phones," in *Proceedings of the International Conference on Multimedia*, ser. MM. New York, NY, USA: ACM, pp. 787–790, October 2010.

[9] J. Yim, C. Park, J. Joo, and S. Jeong, "Extended Kalman filter for wireless LAN based indoor positioning," *Decision Support Systems*, vol. 45, no. 4, pp. 960 – 971, March 2008.

[10] F. Lassabe, P. Canalda, P. Chatonnay, and F. Spies, "Indoor Wi-Fi positioning: techniques and systems," *annals of telecommunications - annales des télécommunications*, vol. 64, no. 9-10, pp. 651–664, October 2009.

[11] Z. Yang, C. Wu, and Y. Liu, "Locating in fingerprint space: Wireless Indoor Localization with little human intervention," in *Proceedings of the 18th Annual International Conference on Mobile Computing and Networking*, ser. Mobicom. New York, NY, USA: ACM, pp. 269–280, August 2012.

[12] F. Gustafsson and F. Gunnarsson, "Mobile positioning using wireless networks: possibilities and fundamental limitations based on available wireless network measurements," *Signal Processing Magazine, IEEE*, vol. 22, no. 4, pp. 41–53, July 2005.

[13] F. Gunnarsson, F. Lindsten, and N. Carlsson, "Particle filtering for network-based positioning terrestrial radio networks," in *Data Fusion Target Tracking 2014: Algorithms and Applications (DF TT), IET Conference on*, pp. 1–7, April 2014.

[14] C. Botteron, M. Fattouche, and A. Host-Madsen, "Statistical theory of the effects of radio location system design parameters on the positioning performance," in *Vehicular Technology Conference. Proceedings. VTC IEEE 56th*, vol. 2, pp. 1187–1191, Fall-2002 .

[15] J. MacDonald, D. Roberson, and D. Ucci, "Location estimation of isotropic transmitters in wireless sensor networks," in *Military Communications Conference. MILCOM IEEE*, pp. 1–5, October 2006.

[16] P. Bahl and V. N. Padmanabhan, "RADAR: an in-building RF-based user location and tracking system." *INFOCOM*, page 775-784., March 2000.

[17] N. Patwari, J. Ash, S. Kyperountas, A. Hero, R. Moses, and N. Correal, "Locating the nodes: cooperative localization in wireless sensor networks," *Signal Processing Magazine, IEEE*, vol. 22, no. 4, pp. 54–69, July 2005.

[18] J. Yin, Q. Yang, and L. Ni, "Learning adaptive temporal radio maps for signal-strength-based location estimation," *Mobile Computing, IEEE Transactions on*, vol. 7, no. 7, pp. 869–883, July 2008.

[19] P. Tarrío, A. M. Bernardos, and J. R. Casar, "Weighted least squares techniques for improved Received Signal Strength Based localization," *Sensors*, vol. 11, no. 9, pp. 8569–8592, August 2011.

[20] M. Hata, "Empirical formula for propagation loss in land mobile radio services," *IEEE Journal Vehicular Technology*, vol. 29, no. 3, pp. 317–325, August 1980.

[21] E. Damasso and L. M. Correia, Eds., *Digital mobile radio towards future generation systems*. Brussels, Belgium: European Cooperation in the field of Scientific and Technical research (COST), 1999.

[22] T. Rappaport, *Wireless Communications: Principles and Practice*, 2nd ed. Upper Saddle River, NJ, USA: Prentice Hall PTR, 2001.

[23] F. Gunnarsson, M. Johansson, A. Furuskar, M. Lundevall, A. Simonsson, C. Tidestav, and M. Blomgren, "Downtilted base station antennas - a simulation model proposal and impact on HSPA and LTE performance," in *Vehicular Technology Conference. VTC IEEE 68th*, pp. 1–5, Sept 2008.

[24] Linkoping University, Sweden. (2014, Dec.) Sensor fusion app. [Online]. Available: https://play.google.com/store/apps/developer?id=Sensor+fusion+at+Link%C3%B6ping+University