Estimation of Isotropic Pathloss from Directional Channel Measurements in Azimuth and Elevation

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Abstract—**Path-Loss is one of the essential characteristics of wireless propagation channels. It is usually captured from channel measurements with (quasi-) isotropic antennas. To characterize the wireless channels at high frequencies, beamforming or directional antennas are commonly used, in which case a method for estimating the isotropic path-loss is needed. The method should account for the possible spatial overlap of the different directional measurements while including the received signal from all the multipath components (MPCs) in the channel. In this letter, we propose an efficient method that uses a weighted sum of the powers received from the directional measurements. The weights can be calculated using matrix inversion. We verify the solution using synthetic data and demonstrate the usage with measurements at sub-THz frequencies.**

I. Introduction

Path Gain (PG), the inverse of Path Loss (PL),[1] is one of the essential quantities for characterizing a wireless propagation channel [1]. It refers to the ratio of the received power over the transmit power, averaged over fading. Extensive studies have been dedicated to systems and methods to capture the PG in different frequency bands and environments. Ideally, the reported PG values should be independent of the used measurement (sounding) systems. This allows for the utmost generality and for a fair comparison with other studies. To achieve this, proper system calibration is usually performed to eliminate the impact of the RF characteristics of the system. Furthermore, since PG is generally defined in the absence of antenna directionality, to capture the received energy from all the possible directions, isotropic or omni-directional antennas (or reasonable approximations thereof) should be used; we refer to the resultant PG as Isotropic PG (IPG).[2]

Many channel measurements, in particular at high frequencies, use beamforming or directional antennas, either to emulate the actual operation of communications systems that use directional antennas, or to obtain better Signal to Noise Ratio (SNR) of the measurements, or because the measurements also aim to obtain the directionally resolved channel characteristics. While the directional PG can be easily computed from such measurements, it is a quantity that depends on beamwidth (BW) and orientation of the antennas, thus making it difficult to compare between measurements performed with different antennas. Thus methods to reconstruct the IPG from directional measurements are needed.

Various methods have been proposed in the literature to tackle this problem. One popular method reconstructs the IPG by summing the received power from measurements with the antennas pointing in different directions and subtracting the gain of summed pattern, e.g., [3], [4]. Ref. [3] shows that this method is sufficient for *uniform* measurements in symmetric beam patterns. However, when these conditions are not fulfilled, over- or under-weighing different MPCs may occur. Alternatively, the parameters of the MPCs are estimated, e.g., via high-resolution parameter estimation such as SAGE [1], followed by adding up their powers, but this has the drawback of sensitivity to noise and model errors and computation complexity. Ref. [5], uses the power delay profile (PDP) to find, for each delay bin, the MPC with the maximum power over the different horn antenna orientations, but as pointed out in [6], this method does not account for all the paths in the channel (especially diffuse scattering). Ref. [6] proposes, for measurements in a single elevation, a method that extracts peaks in the angle delay spectrum and corrects for the diffuse scattering. Recently, [7] proposed an enhancement to the measurement setup via a virtual antenna array with directional antennas for narrow beams with small sidelobes for better path identification. Different from the above, this work proposes an efficient post-processing method suited for measurements with asymmetric beam patterns and nonuniform sampling. The method first constructs the equivalent gain matrix, which is then used to calculate *linear* weights to combine the *average* energy received in *all* the directions and mostly avoids under- or over-weighting. We compare the estimated IPG to "true" IPG in a synthetic environment, where the ground truth is known. We also demonstrate the method's applicability over a sample route in a double-directional THz measurement campaign.

II. Propagation Channel preliminaries

The channel frequency response at frequency f including the complex antenna patterns at the receiver (RX) and trans-

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[1]Given the relation of PG and PL, we continue the discussion using PG.

[2]This is comparable to the *Basic Transmission Loss "L_b"* defined in ITU recommendation R-Rec-P.341-5-199910 [2]. In this case, the IPG refers to pathloss where contributions of all MPCs are added up irrespective of azimuth or elevation, i.e., the antenna pattern is truly isotropic. From a practical point of view, it is sufficient if the pattern is omnidirectional in azimuth and isotropic over the elevation range in which significant MPCs occur. Often, omnidirectional antennas like dipoles are sufficient; in this paper we will use "isotropic" and "omnidirectional" interchangeably.

mitter (TX) sides, respectively, g and b, can be written as

$$h(f)=\sum\nolimits_{l=1}^{L}\alpha_l g(\phi_l^a,\theta_l^a)b(\phi_l^d,\theta_l^d)e^{-j2\pi f\tau_l}, \qquad (1)$$

where L is the number of MPCs, α_l, τ_l, θ_l and ϕ_l are the complex gain, the delay, the angles in the azimuth and the elevation domains of the l^{th} path. The superscripts $()^a$ and $()^d$ refer to the arrival and departure sides, respectively. Then the IPG can be calculated as

$$P_{\text{G}}\triangleq\sum\nolimits_{l=1}^{L}|\alpha_l|^2. \qquad (2)$$

In other words, the IPG is the sum of all MPCs' power without the antennas' impact. This can be empirically *approximated* with the wideband PG, a function of the system bandwidth, and discussed in more detail below. Here, we will assume they are the same. In the initial analysis, we will focus on one side, without loss of generality, let it be the RX side, so we drop the superscripts in (1) and assume $b(\theta,\phi)=1$.

When the RX end employs a directional antenna (e.g., horn antenna) that is pointed into different directions, the gain of the m^{th} and n^{th} azimuth and elevation positions is:

$$g_{m,n}(\theta,\phi)=g(\phi-\bar{\phi}_m,\theta-\bar{\theta}_n), \qquad (3)$$

where $\bar{\phi}_m$ and $\bar{\theta}_n$ are the m^{th} and the n^{th} angle shifts, $m\in\{1,...,M\}$, and $n\in\{1,...,N\}$. When the antenna is positioned towards the $m^{\text{th}},n^{\text{th}}$ directions, the observed channel is:

$$h_{m,n}(f)=\sum\nolimits_{l=1}^{L}\alpha_l g_{m,n}(\phi_l,\theta_l)e^{-j2\pi f\tau_l}. \qquad (4)$$

To calculate the frequency-independent (wideband) PG (assuming frequency-independent antenna pattern in the range of interest $f\in[f_1,f_{N_F}]$) at a given direction, one might use

$$P_{\text{G}m,n}=\frac{1}{\bar{G}_{m,n}}\frac{1}{N_F}\sum\nolimits_{f=f_1}^{f_{N_F}}|h_{m,n}(f)|^2, \qquad (5)$$

where N_F is the number of the frequency points used, and the bandwidth is assumed to be sufficiently large to average out the Small Scale Fading (SSF), so that cross-MPC terms approximately vanish, $\bar{G}_{m,n}$ is the "effective antenna *power* gain" in that antenna position (to be discussed below). The interpretation and the accuracy of the method depend on two main factors: (i) The distribution of the Angle of Arrivals (AoA's) of the MPCs, and (ii) the antenna pattern.

Note that with omni-directional antennas, with $N=M=1$, and the MPCs concentrated in the azimuth plane,

$$P_{\text{G}_{m,n}}\approx\frac{1}{\bar{G}_{m,n}}\underbrace{\sum\nolimits_{l=1}^{L}|\alpha_l|^2G_{m,n}(\phi_l,\theta_l)}_{P_{m,n}}\approx\sum_{l=1}^{L}|\alpha_l|^2, \qquad (6)$$

where $G_{m,n}(\phi,\theta)\triangleq|g_{m,n}(\phi,\theta)|^2$, and used $G_{m,n}(\phi_l,\theta_l)\approx\bar{G}_{m,n}$ for the last term. When $G_{m,n}(\phi,\theta)$ is a horn antenna with an ideal flat top and sharp gain decay outside the desired BW, the PG value represents the directional PG considering only the MPCs that fall within BW centered at $(\bar{\phi}_n,\bar{\theta}_m)$. However, real horns show a gradual gain decay. is expected. Usually, a 3 dB BW is used to identify the resolution of the antenna/beam, e.g., see Fig. 1. $\bar{G}$ can be *approximated* by the maximum value of $G(\phi,\theta)$, or the average of $G_{m,n}(\phi,\theta)$ within the desired angular range (e.g., the 3 dB BW).

III. The Proposed Solution

A. Problem Statement

The goal of this paper is to calculate the IPG, defined in (2), from measurements with a non-ideal antenna pattern, the antenna's beam center is oriented/rotated in M azimuth and N elevation directions. Since the antenna patterns are not ideal, the received power in each position m,n is a weighted sum of *all* the MPCs, $P_{m,n}=\sum_{l=1}^{L}|\alpha_l|^2G_{m,n}(\phi_l,\theta_l)$, which also represents the average received power as in (6). Although $G_{n,m}(\phi,\theta)$ is known for all m,n, the values ϕ_l,θ_l are unknown. Thus, we wish to extract the IPG from the $P_{m,n}$'s. In the following, we present our proposed method.

B. The Fundamental Algorithm

The proposed method approximates the IPG with a linear combination of the received power from all measurements. As discussed below, in this subsection, we consider a simple case where the antenna rotation in the azimuth plane is uniform; a generalization is provided in the next subsection. We start by rewriting $P_{m,n}$ as follows. Define $S=NM$ mutually exclusive groups of MPCs. Let the set $\mathcal{S}_{m,n}$ and $\Omega_{m,n}$ contain, respectively, the indices and the angles (azimuth and elevations) for the MPCs that fall within the spherical regions where the pattern of the m,n position is maximum, i.e., for all θ_l and ϕ_l the $\mathcal{S}_{m,n}$:

$$\mathcal{S}_{m,n}=\left\{l:G_{m,n}(\theta_l,\phi_l)>G_{m',n'}(\theta_l,\phi_l),m\neq m',n\neq n'\right\}$$

With that, we have $\sum_m\sum_n|\mathcal{S}_{m,n}|=L$, where $|.|$ is the cardinality of a set. Note that the sets $\mathcal{S}_{m,n}$ and $\Omega_{m,n}$ are used only for the derivation. Then,

$$P_{m',n'}=\sum\nolimits_n\sum\nolimits_m\sum\nolimits_{l\in\mathcal{S}_{n,m}}|\alpha_l|^2G_{m',n'}(\phi_l,\theta_l) \qquad (7)$$

Next, let P_{all} be the sum of all the received power in all antenna positions, and using (7) and simple manipulation

$$\begin{aligned}P_{\text{all}}&=\sum\nolimits_{m'}\sum\nolimits_{n'}P_{m',n'} \qquad (8)\\&=\sum\nolimits_n\sum\nolimits_m\sum\nolimits_{l\in\mathcal{S}_{m,n}}|\alpha_l|^2\sum_{m'}\sum\nolimits_{n'}G_{m',n'}(\phi_l,\theta_l).\end{aligned}$$

With uniform shifts in the azimuth plane, $\bar{\phi}_m=m\Delta\bar{\phi}$, $m\in\{0,M-1\}$, i.e., $M\Delta\bar{\phi}=2\pi$ to cover the azimuth plane, and assuming the patterns will add up to omni,[3] one can observe that every MPC will be amplified by approximately the same gain in azimuth; thus we assume $G_{n'}(\theta_l)\approx\sum_{m'}^{M}G_{m',n'}(\phi_l,\theta_l)$, and use elevation measurements

$$P_n=\sum\nolimits_m P_{m,n}. \qquad (9)$$

[3]If this is not fulfilled, a modified approach is required (see Sec. III-C2). While this may occur in either azimuth or elevation (or both), we demonstrate this here for the example of the elevation pattern since many practical systems (e.g., sounding systems) are designed to cover only parts of the elevation range and thus may violate the condition.

Consequently, we can redefine the groups based on elevations only, i.e., we have N MPCs groups with indices in $\mathcal{S}_n$ and elevation angles in Ω_n. Also, we can write P_{all} as

$$P_{\text{all}} = \sum\nolimits_{n'} P_{n'} \approx \sum\nolimits_{n} \sum\nolimits_{l \in \mathcal{S}_n} |\alpha_l|^2 \sum_{n'} G_{n'}(\theta_l). \quad (10)$$

Simplifying further with $G_{n'}(\theta_l) \approx G_{n',n}$ $\forall \theta_l \in \Omega_n$, i.e., the gain is approximately constant in the main region of the n^{th} group (e.g., mean or max. of power pattern in a given region). Note that, different from $\bar{G}_{m,n}$, $G_{n',n}$ is a function of the antenna orientation and the group. We have

$$P_{\text{all}} \approx \sum_{n}^{N} \sum_{l \in \mathcal{S}_n} |\alpha_l|^2 \sum_{n'}^{N} G_{n',n} = \sum_{n}^{N} \sum_{n'}^{N} G_{n',n} P_{\text{g},n}. \quad (11)$$

In the last equality, we defined $P_{\text{g},n} \triangleq \sum_{l \in \mathcal{S}_n} |\alpha_l|^2$. With (10), and the fact that $P_{\text{G}} = \sum_{n}^{N} P_{\text{g},n}$, a linear system of equations captures the relation between $P_{\text{g},n}$ and P_n as:

$$\mathbf{P} = \mathbf{K}\mathbf{P}_{\text{g}}, \quad (12)$$

where $\mathbf{P}_{\text{g}} = [P_{\text{g},1}, ..., P_{\text{g},N}]^\top$, $\mathbf{P} = [P_1, ..., P_N]^\top$ and

$$\mathbf{K} = \begin{bmatrix} G_{1,1} & ... & G_{1,N} \\ \vdots & \vdots & \vdots \\ G_{N,1} & ... & G_{N,N} \end{bmatrix}. \quad (13)$$

Note that $\mathbf{P}$ is known from the measurement (from (9)), and $\mathbf{K}$ can be calculated from the antenna pattern (see Fig. 3 for an example). We can then solve for $\mathbf{P}_{\text{g}}$ and calculate P_{G}:

$$\mathbf{K}^{-1}\mathbf{P} = \mathbf{P}_{\text{g}}, \quad \text{thus} \quad P_{\text{G}} = \underbrace{\mathbf{1}_{N\times 1}^\top \mathbf{K}^{-1}}_{\boldsymbol{\omega}^\top} \mathbf{P}, \quad (14)$$

where $\mathbf{1}_{N\times 1}$ is $N \times 1$ all one vector, and $()^\top$ is the transpose operation, and $\boldsymbol{\omega}$ is $N \times 1$ vector of combing coefficients.

C. Generalizations

In the above, we have ignored the structure of the TX antenna by assuming $b(\theta, \phi) = 1$ and focused on multi-elevation measurements with uniform rotation of the RX antenna in the azimuth plane. However, the method can be generalized to the MIMO system and a non-uniform rotation in the azimuth plane (as long as the pattern does not change significantly within the $|\bar{\phi}_{m+1} - \bar{\phi}_m|$). We briefly discuss the MIMO case we use in Sec. IV and the non-uniform rotation.

1) MIMO: Assume that the TX can rotate its antenna into V and U directions in the azimuth and elevation, respectively; for each TX antenna position (v, u), the RX measures the power at all RX antenna orientations. The method above can be applied using three steps:

1. Identify the PG value at the RX side by following (9) (13) and (14). Denote this as $\mathrm{P}_{\mathrm{G}u,v}$.
2. With uniform antenna rotation in azimuth at the Tx side, let $\mathrm{P}_{\mathrm{G}u} = \sum_{v}^{V} \mathrm{P}_{\mathrm{G}u,v}$, which will be the total power received in a given elevation cut u.
3. Apply the same method as eq. (14). However, we have to replace $\mathbf{P}$ with $\mathbf{P}_{\text{TX}} = [\mathrm{P}_{\mathrm{G}1}, ..., \mathrm{P}_{\mathrm{G}U}]^\top$, and $\mathbf{K}$ with $U \times U$ matrix $\mathbf{B}$, that can be constructed as $\mathbf{K}$ but with TX beam pattern (b). The solution:

$$P_{\text{G}} = \mathbf{1}_{U\times 1}^\top \mathbf{B}^{-1} \mathbf{P}_{\text{TX}}, \quad (15)$$

will be equivalent to a PG measurement using omni-directional antennas at both link ends.

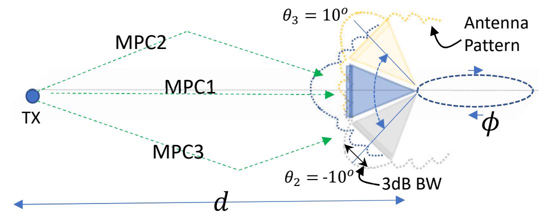

Fig. 1: The setup for synthetic data. A TX and an RX with a horn antenna. To construct $\mathbf{K}$ based on uniform azimuth measurements (used in Sec. IV), we need to rotate and sum the pattern gain (to obtain G_n) with $\Delta\bar{\phi}$ shifts ($= 10^o$ here) in a given elevation shifts $\bar{\theta}_n (\in \{0, -10^o, 10^o\})$. Note $G_{n,i}$ can be the max. (or average) of the summed gain $(n-i)\Delta\bar{\theta}$ away from the center of elevation center.

2) Non-Uniform Measurements: We mention briefly that when the rotation of the antenna/beam is not uniform, all the three components of (14) should be updated, such that $\mathbf{P}$ is an $NM \times 1$ vector that represents the received power by each antenna orientation, and $\mathbf{K}$ is $NM \times NM$ matrix of the antennas gains in all positions, where each MPC groups defined by $\mathcal{S}_{m,n}$ and $\Omega_{m,n}$ would be represented by $\bar{\theta}_{0,n}$ and $\bar{\phi}_{0,m}$, and $G_{i,j} = G_{m',n'}(\bar{\phi}_{0,m}, \bar{\theta}_{0,n})$, where $i, j \in \{1, ..., NM\}$, and i and j have one-to-one mapping to the possible (m', n') and (m, n), respectively.

D. Known Limitations

We point out a few limitations to the proposed approach: (i) the dependency on bandwidth (or repeated measurements) to eliminate SSF, (ii) the dependency on the quality of $G_{n',n}$ approximation. This might depend on local smoothness of the pattern and the distribution of the AoA (and/or angle of departure) within the angular bins. For extremely asymmetric patterns (e.g., maximum gain not in the "0 degree" bin), negative weights can occur, which – in combination with insufficient averaging out of the SSF – may lead to nonphysical PG values. And (iii) the need for matrix inversion. Finally, note that in case of $\sum_{m,n} G_{m,n}(\phi, \theta)$ is approximately constant for all ϕ and θ (over the angular range of MPCs), the sum of patterns method ("Pattern-Sum") will perform best. Our method shows advantages when this condition is not fulfilled.

IV. Validation

To validate the proposed methods we use synthetic data. For *demonstration*, we also apply the method to measured data in the THz frequency band. Again, following the convention, the results are presented as PG (the inverse of the PL).

A. Validation with Synthetic Data

The reason for choosing synthetic data to validate the results is the fact that we can obtain a large number of realizations to evaluate the *distribution* (CDF) of the IPG over numerous

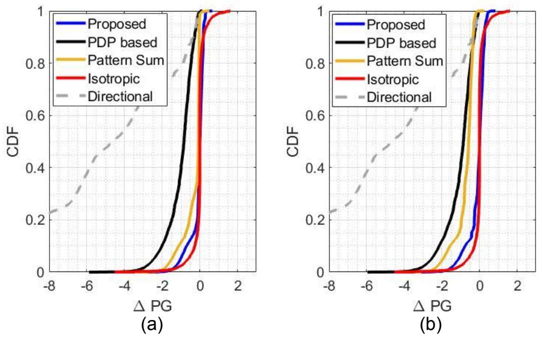

Fig. 2: The CDF of the PG (inverse of PL) estimation error to the true IPG, when: the used horn antenna is (a) symmetric (b) distorted (non-symmetric), see Fig. 3-(b).

settings. In particular, we consider the scenario in Fig. 1, where an RX is at a distance d from a TX. The RX uses a horn antenna (or beam-pattern) that follows Fig. 3; note that without a loss of generality, we normalize the gain to one for this section. The antenna rotates uniformly in azimuth and over three elevation angles. We consider five cases for d, in four cases $d \in \{5, 10, 20, 100\}$m, and in another case, it is random up to 100m. We also vary the number of MPCs in this study $L \in \{1, 3, 7, 30\}$, the excess run length is distributed uniformly in $[0, d]$; we assume that the power of each MPC follows the Free Space Path Gain (FSPG), and the delay is equal to its run-length. The phases of the MPCs are generated randomly. Furthermore, the AoA distribution in ϕ is assumed to be uniform, i.e., $\phi_l \sim \mathcal{U}[0, 2\pi]$, in elevation $\theta_l \sim \mathcal{U}[-\frac{\theta_{max}}{2}, \frac{\theta_{max}}{2}]$, where $\theta_{max} \in \{10^o, 30^o, 60^o, 90^o\}$, note that $\theta = 0$ is the horizontal plane. Then, the received signal can be written as in (1). The large bandwidth of 2GHz results in good SSF averaging. For obtaining a CDF of the IPG, 100 channel realizations are generated.

The results are shown as CDF of the deviation from the ground truth and are compared to: (i) summing up all the power from all the directions and normalize by pattern sum (ii) using the directional PDPs to identify the MPC per delay bin, (iii) received power with *an* isotropic antenna, we also show the directional PG as a reference. Fig. 2 shows the results. In Fig. 2-(a), the proposed method and the Pattern Sum perform similarly well, while the PDP method shows larger bias. The two baselines show more bias or variation. The PG with an isotropic antenna differs from the ground truth because of insufficient SSF averaging due to the finite BW. Fig. 3-(b) considers the case when the pattern is non-symmetric (e.g., distorted), such that the pattern is lower by a factor of 0.7 for $\theta < -15^o$, see, compared to the symmetrical case. In this case, the proposed method is still unbiased, with a slight increase in the standard deviation compared to isotropic measurements. The Pattern Sum method shows bias because the assumptions (omni-like effective pattern) in its derivation are not fulfilled in this setup. The PDP based method shows bias as well.

B. Demonstration with Measurement Data

We carried out a small measurement campaign in the 140 GHz band in an outdoor urban scenario. Our environment is

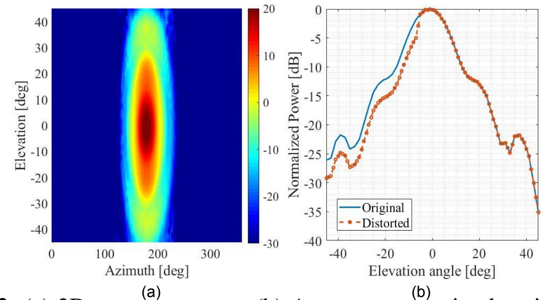

Fig. 3: (a) 3D antenna pattern. (b) Antenna pattern in elevation with and without distortion.

TABLE I: Measurement Parameters

Variable	Values
Carrier Freq.	140.5 GHz
Bandwidth/ Freq. resolution	1 GHz /1 MHz
Ant. Pattern and BW	Horn/13^o
Transmitted Power	0 dBm
TX/RX heights	1.65 m
Number of TX/RX Locations	1/4
TX-RX Separation Distances	$\{1, 2, 5, 15\}$ m

located at the entrance of the "VHE" building on the USC campus. It is an open space area with interspersed pillars. The measurement is done on a linear route, and the separation distance and other parameters are summarized in Table I, for more details see [8]. The azimuth and elevation step width are, respectively, $\Delta\bar{\phi} = \Delta\bar{\theta} = 10^o$. We use one elevation at the TX side and three elevations at RX side and full azimuth rotations on both sides. The PG results are shown in Fig. 4.

We compare the proposed method with SIMO and MIMO to SISO, FSPG, and the methods of PDP based and Pattern Sum. The SISO is calculated using pairs of directional antennas with maximum power. Since at short distances the LOS path dominates all possible reflections we see comparability to FSPG. However, at longer distances, we start to observe that (i) SISO slightly under-estimates path gain, (ii) our proposed SIMO and MIMO capture more energy due to possible reflections that an omni antenna would ideally observe, the observed deviation is about 2dB at the 15m, [8]. Finally, as above, the other baselines show differences of around 1 dB.

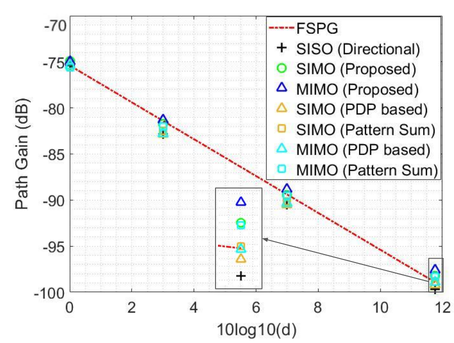

Fig. 4: Demonstration with measurements in THz band.

V. Conclusions

This paper proposes an efficient method to estimate the isotropic PL (PG) from directional measurements. For given antenna (beam) patterns, the method linearly combines the weighted average received signal in all measured directions. The method is validated with synthetic and measured data.

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