Abstract—In this paper we investigate the possibility of modeling a single antenna alone and in close proximity to a physical object by means of discrete point source scatterers. The scatter point model allows joint modeling of a physical antenna and the human body as a single extended object with direction dependent scattering coefficients for the scatter points. We introduce the term extended antenna describing antenna and human body together. To investigate the identifiability of the model parameters we make use of ultrawideband channel measurements and accurate ground truth position and orientation measurements obtained with an optical tracking system. By comparing measurements of the antenna attached directly to the user with measurements for the antenna without the user nearby, we show the shadowing and scattering effects of the human body and the antenna.

Index Terms—channel modeling, ultrawideband, off-body measurements.

I. INTRODUCTION

For positioning applications, an accurate model of the received signal is needed. This model should include any environment-related effects that can affect an estimator of position related signal parameters from the received signal. Such effects can be specular multipath components (SMCs) and a diffuse multipath component (DMC) [1] or scattering objects such as mobile users [2] or trees, e.g., for GNSS signals [3]. Especially blockage of the line-of-sight propagation path can introduce a strong bias in delay estimates, a survey of which is presented in [4]. This is especially true in off-body communications, where the anchor or the agent are in close proximity to the user [5], [6]. The effects of wearable antennas on narrowband signals were already investigated in [7], [8] highlighting the strong shadowing effect introduced by the human body. As shadowing alone is not sufficient to accurately model effects on wideband signals, it is of interest to develop suitable channel models incorporating both shadowing and dispersion in the delay-angle domain.

In [9] we have shown that a user equipped with an agent can be modeled as an extended object (EO) using a measurement based, empirically chosen scattering point distribution and a gain function. In this paper we investigate the possibility of calibrating the statistical model and show that the joint description of scattering object and non-ideal antenna is implicitly possible with the proposed model from [9]. We model agent and user as one EO under the term extended antenna (EA), adding components via point source scatterers jointly modeling the dispersive effects of antenna and user. The general setup under investigation is shown in Fig. 1 with the EA denoted by \( S \) and the reference direction for the angle of arrival (AOA) \( \phi \) included as well.

For estimation and tracking of the shape of EOs, a large number of algorithms exist [10]–[13], which usually require a large number of (spatial) measurements (e.g., obtained using LIDAR sensors [11]) to accurately estimate the object’s state. As highly accurate spatial measurements using radio signals require large antenna arrays and a large measurement bandwidth, state of the art algorithms are not directly applicable. This paper shows that a suitable measurement setup allows estimation of scattering points to calibrate the model.

The rest of the paper is structured as follows: Section II describes the system and signal model, Section III introduces the measurement campaign and the estimation procedure. Results are shown in Section IV and Section V concludes the paper.

II. SYSTEM MODEL AND SIGNAL MODEL

A. System Model

We consider a single anchor at known position \( \mathbf{a} = \begin{bmatrix} x_a \\ y_a \end{bmatrix} \in \mathbb{R}^2 \) and an agent at position \( \mathbf{p} = \begin{bmatrix} x \\ y \end{bmatrix} \in \mathbb{R}^2 \),
each equipped with a single antenna (see Fig. 1). The EA $S = \{\mu, \Sigma, Q\}$ is described by mean position $\mu = [x_S, y_S]^T \in \mathbb{R}^2$ with the covariance matrix $\Sigma \in \mathbb{R}^{2 \times 2}$ denoting the shape in terms of a covariance matrix. Scattering points $q_j = [x_j, y_j]^T \in \mathbb{R}^2$ belonging to the EA $S$ are modeled as a marked Poisson point process (MPPP) denoted by $Q = \{(q_1, \beta_1), (q_2, \beta_2), \ldots \} = \{(q_j, \beta_j)\}$ where $j$ is an index solely used to distinguish points and $\beta_j \in \mathbb{C}$ is the complex mark of the corresponding scattering point $q_j$. Per definition of an MPPP, the number of points in $Q$ is Poisson distributed with mean $N(Q)$, with the points spatially distributed in the EA shape according to an intensity function $\rho(q)$. A thorough treatment of point process theory can be found in [14]. The extension of the model to 3-dimensions is straightforward.

**B. Signal Model**

The signal at the agent is modeled to consist of a deterministic and a stochastic part. The former contains $K$ specular multipath components (SMCs), e.g., modeled by an image source model [15]. The latter contains a scattered component (SC) and a diffuse multipath component (DMC) modeling the environment randomness. The SC is modeled by the MPPP $Q$ described above and the DMC by a random process $\nu(\tau)$ with a suitable delay-angle power spectral density, see, e.g., [11], [16]. We are only interested in effects on the line-of-site (LOS) path between anchor and agent, i.e., without loss of generality we set $K = 1$ and neglect the DMC. This gives the radio channel as

$$ h(\tau; p) = \alpha \delta(\tau - \tau(p)) + \sum \beta_j \delta(\tau - \tau(q_j) - \tau(p - q_j)) $$

where $\alpha \in \mathbb{C}$ is the complex LOS amplitude and $\beta_j \in \mathbb{C}$ the complex scattering coefficient of scattering point $q_j$. The path delays are $\tau(p) = \frac{1}{2}\|p - a\|$ where $\| \cdot \|$ denotes the vector norm and $c$ is the speed of light.

The signal $r(t)$ received at the agent when transmitting a baseband pulse $s(t)$ at carrier frequency $f_c$ is given by

$$ r(t) = \int s(t - \tau(p))e^{-j2\pi f_c \tau}h(\tau; p)d\tau + n(t) $$

$$ = \alpha s(t; p) + \sum \beta_j s(t; p, q_j) + n(t) $$

where $s(t; p) = s(t - \tau(p))e^{-j2\pi f_c \tau(p)}$ is the pulse received at position $p$ and $s(t; p, q) = s(t - \tau(p - q); q)e^{-j2\pi f_c \tau(a - q)}$ the pulse received at $p$ after scattering at $q$. The measurement noise $n(t)$ is modeled as zero-mean complex additive white Gaussian noise (AWGN) with double-sided power spectral density $\frac{N_0}{2}$. Synchronous sampling of (2) with frequency $f_s = \frac{1}{T}$ over an observation interval $T$ and stacking the samples in the vector $r \triangleq [r(0), r(T), \ldots, r((N-1)T)]^T \in \mathbb{C}^N$ and $N = T/T_s$ yields the discrete-time signal model

$$ r = \alpha s(p) + \sum \beta_j s(p, q_j) + n \in \mathbb{C}^N $$

$$ \triangleq \alpha s(p) + S(p, Q)\beta + n $$

where $\beta = [\beta_1, \ldots, \beta_J]^T \in \mathbb{C}^J$ and $S(p, Q) = [s(p, q_1), \ldots, s(p, q_J)] \in \mathbb{R}^{N \times J}$ where $J$ denotes the number of components for a specific realization of $Q$. Scattering point positions are combined into $Q = \{q_1, \ldots, q_J\}$ and the columns of $S(p, Q)$ are defined as $s(p) \triangleq [s(0; p), \ldots, s((N-1)T_s; p)]^T \in \mathbb{C}^N$ and $s(p, q) \triangleq [s(0; p, q), \ldots, s((N-1)T_s; p, q)]^T \in \mathbb{C}^N$. The vector $n$ contains the AWGN noise samples with covariance matrix $C \triangleq E[nn^H] = \sigma_n^2 I_N$, $\sigma_n^2 = \frac{N_0}{2T_s}$ and $I_N$ is an $N \times N$ identity matrix.

The model in (4) can be interpreted as a standard multipath model with $J + 1$ components: the LOS path directly arriving at the agent $p$ from the anchor $a$ and $J$ components that are paths scattered at locations $q_j$. The according likelihood function of the model is

$$ f(r; p, \alpha, Q, \beta) \propto \exp\left(-\|r - \alpha s(p) - S(p, Q)\beta\|^2\right). \quad (5) $$

Due to the large number of model parameters, estimation of all parameters might not be possible, depending on the measurement setup. The following section describes a measurement procedure to allow calibration of $\beta$ and $Q$ by forming a synthetic array assuming a known agent position $p$.

**III. MEASUREMENT SETUP AND MODEL CALIBRATION**

To calibrate the model ultrawideband measurements were performed alongside ground truth position and orientation measurements of the agent and parts of the user, obtained using an optical tracking system (OTS) with position and orientation accuracy below 1 mm and 1° respectively. This setup allows using a synthetic array of anchors to formulate a non-coherent estimation procedure of scattering points and coefficients.

**A. Measurement Setup**

The radio measurements were performed with a correlation channel sounder (CS) covering a frequency range of $f = 3.8$–10.2 GHz with $f_c = 6.95$ GHz allowing fully coherent measurements. The measurement system was calibrated, including CS, cables and connectors (but not the antennas). The antennas used were a taqglas FXUWB10 patch antenna as agent (see Fig. 2a) and a dipole antenna [17] App. B.3] as anchor, both suitable for the measurement frequency range. The dipole antenna has a sufficiently flat pattern in the horizontal plane with strong attenuation towards floor and ceiling, reducing floor and ceiling reflections. Both devices are positioned at similar height.

The anchor position was fixed throughout the measurements, with the agent positioned at various on-body positions (see Fig. 3a) on a user performing a full rotation on the spot with a static posture and static on-body position of the agent, while recording $M = 200$ channel responses. An overview of the on-body positions is shown in Fig. 3a alongside the coordinate system used in the evaluation. The floorplan of the measurement setup is shown in Fig. 2b, indicating the measurement setup is shown in Fig. 2b, indicating the coordinate system used in the evaluation. The floorplan of the on-body positions is shown in Fig. 3a alongside the coordinate system used in the evaluation.
allows to jointly use all $M = 200$ measurements obtained during a rotation of the user, simulating a synthetic array by fixing the agent device (and thus the EA) and moving the anchor at (synthetic) positions $\alpha_m$ on a circle centered around the agent (see Fig. 2b). Note that this is only valid for investigation of the LOS.

### B. Model Calibration

To calibrate the model parameters we make use of the available ground truth anchor and agent positions and apply a maximum likelihood (ML) estimator to directly estimate scatter point positions. The underlying assumption is that due to the static posture and on body position, only one realization of the EA is observed during the $M$ measurements. Assuming furthermore that all measurements $r_m$ are independent with identical noise variance $\sigma^2_w$, allows using (5) to write the joint likelihood of all measurements as

$$
f(r; p, \alpha, Q, \beta) = \prod_{m=1}^{M} f(r_m; p, \alpha_m, Q, \beta_m)$$

where $r = [r_1^T, \ldots, r_M^T]^T$, $\alpha = [\alpha_1, \ldots, \alpha_M]^T$, $\beta = [\beta_1^T, \ldots, \beta_M^T]^T$ are the stacked signals, LOS amplitudes and scattering coefficients for all $M$ measurement. Based on (6) the resulting ML estimator is obtained as

$$\hat{\alpha}, \hat{\beta}, \hat{Q} = \arg\max_{\alpha, \beta, Q} \prod_{m=1}^{M} f(r_m; p, \alpha_m, Q, \beta_m).$$

To optimize (7), the LOS amplitudes and scattering coefficients are estimated separately for each measurement $m$ as linear least squares (LS) estimates [18] denoted by $\hat{\alpha}$ and $\hat{\beta}$ using the known ground truth agent position $p_t$ available from the OTS [7]. These estimates can be interpreted as non-parametric estimates of the user shadowing and agent antenna pattern, modeling the full gain pattern of the EA. Delay dispersion of the user and the agent antenna is in turn modeled by the scattering points. To find estimates of scattering points $Q$ we employ a simple procedure which greedily maximizes (6) by adding scattering points consecutively (i.e., without joint optimization) as long as the likelihood value can be increased. The chosen stopping criterion is by no means optimal and was chosen heuristically. Even though more sophisticated algorithms could be used, the effect of the human body and the antenna alone can be compared nonetheless as we apply the same algorithm to measurements of the agent with and without user, with (possible) estimation artifacts arising in both cases. An overview of the described iterative ML procedure is given in Algorithm 1.

### IV. RESULTS

Fig. 4 shows the scattering point estimates $Q$ (denoted by blue x) obtained using Algorithm 1 for the agent at different on-body positions (see Fig. 3a). The size of the scattering point visualizes the respective average scattering coefficient magnitude $\beta_j$ of the $j$th scattering point, defined as

$$\hat{\beta}_j = \frac{1}{M} \sum_{m=1}^{M} |\hat{\beta}_{m,j}|$$

with $\hat{\beta}_{m,j}$ being the estimated scattering coefficient of measurement $m$ and scattering point $j$. An identical definition is

**Algorithm 1: iterative estimation procedure**

**Initialization:**
- $\hat{\alpha} = [\alpha_1, \ldots, \alpha_M]^T \leftarrow \hat{\alpha}_m = \frac{s(p_m)^H r_m}{s(p_m)^H s(p_m)} \quad \forall m$;
- $j = 0$;

**Iterations:**
- $j \leftarrow j + 1$;
- find $\hat{q}_j = \arg\max_q \sum_{m=1}^{M} \log f(r_{m,j}; p_t, \hat{\alpha}_m, q, \hat{\beta}_m)$;
- using $r_{m,j} = r_m - s(p_t)^H \hat{\alpha}_m - \sum_{j=1}^{j} s(p_t, q_j)\hat{\beta}_{m,j}$;
- using $\hat{\beta}_{m,j} = ||s(p_t, q_j)||^{-2} s(p_t, q_j)^H r_{m,j}$;
- $\hat{\beta}_j \leftarrow [\hat{\beta}_1, \ldots, \hat{\beta}_{M,j-1}] \leftarrow \hat{\beta}_{m,j}$;
- $Q^{(j)} \leftarrow [q_1, \ldots, q_{j-1}] \leftarrow q_j$;

while $\log f(r_t; p_t, \hat{\alpha}, Q^{(j)}, \hat{\beta}^{(j-1)}; Q^{(j)}) < \log f(r_t; p_t, \hat{\alpha}, Q^{(j)}, \hat{\beta}^{(j-1)}; \hat{Q}^{(j)})$.

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1 This is a valid assumption as the measurements were performed in a short time frame with the measurement device in continuous use.

2 Anchor positions $\alpha_m$ are also obtained by the OTS and assumed known in the signal model as usually the case in positioning applications.
We include the scattering point covariance matrices for each on-body position from the center upper torso. By observing Fig. 4a and 4b, the orientation of the covariance ellipses shows a slight correspondence to the employed on-body position, i.e., when completely blocking the LOS in the reference agent shows a strong increase in pulse dispersion in these directions, which is directly modeled by the larger scattering coefficient magnitudes, observable in Fig. 5a when comparing the on-body positions, the pattern of LOS magnitude and the scattering coefficient magnitude is of similar shape but slightly rotated. Note that this rotation of AMR or PAR is in the opposite direction w.r.t. the rotation of the agent position from the center upper torso. By observing Fig. 4a and 4b, a possible explanation for this effect can be given by the following: Moving the agent towards the left side of the upper torso and thus closer to the left hand/shoulder results in earlier shadowing by the left hand/shoulder, corresponding to earlier shadowing from positive AOAs. The same reasoning holds for position R. For increased AOAs the scattering coefficient magnitudes decrease much faster than the LOS magnitude supporting the effect of lower pulse dispersion with AOAs close to 90° before total blockage as observed in [9].

Fig. 5 shows the squared LOS magnitude (black) and squared average scattering coefficient magnitude of strongest (red) and second strongest (blue) average scattering coefficient magnitude plotted over angle of arrival \( \varphi \). Quantities shown are averaged in 36 non-overlapping uniform angular sectors.
different measurements of the same measurement campaign) and the application of this model in positioning and tracking algorithms with the goal of reducing the influence of the human body on the positioning quality.

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