Optimal Antenna Placement for Two-Antenna Near-Field Wireless Power Transfer

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Abstract—Current trends in communication system design precipitate a change in the operating regime from the traditional far-field to the radiating near-field (Fresnel) region. We investigate the optimal transmit antenna placement for a multiple-input single-output (MISO) wireless power transfer (WPT) system designed for a three-dimensional cuboid room under line-of-sight (LoS) conditions in the Fresnel region. We formulate an optimisation problem for maximising the received power at the worst possible receiver location by considering the spherical nature of the electromagnetic (EM) wavefronts in the Fresnel region while assuming perfect knowledge of the channel at the transmitter. For the case of two transmit antennas, we derive a closed-form expression for the optimal positioning of the antennas which is purely determined by the geometry of the environment. The analytical solution is validated through simulation. Furthermore, the maximum received power at the locations yielding the worst performance is quantified and the power gain over the optimal far-field solution is presented. For the considered cuboid environment, we show that a distributed antenna system is optimal in the Fresnel region, whereas a co-located antenna architecture is ideal for the far-field.

I. INTRODUCTION

Future communication systems are moving towards operating at higher frequencies, as the associated large bandwidth helps support the ever-increasing requirements on data rate, low latency, network heterogeneity, as well as energy efficiency. This precipitates a change in the operating regime from the traditional far-field to the radiating near-field (Fresnel) region, which must be reflected in the modelling of the wireless channel [1]. Wireless systems designed for the Fresnel region are of interest not only for communications [2], but also for wireless power transfer (WPT) [3]. WPT systems designed for the Fresnel region are capable of focusing the energy beams for transferring power wirelessly, thus yielding a larger amount of received power and causing less energy pollution in unwanted directions compared to traditional far-field approaches [1], [3].

A key difference between the far-field and the radiating near-field is how the electromagnetic (EM) wavefronts are modelled. While a planar wavefront model (PWM) is suitable for the far-field, considering the spherical nature of the EM wavefronts is indispensable in the Fresnel region [1]. Therefore, the design of wireless systems for the radiating near-field is driven by the spherical wavefront model (SWM) [1–3]. The SWM has been considered for WPT in [4] where a dynamic metasurface antenna is employed to maximise the weighted sum of received energies via beam focusing.

While the study of WPT in the Fresnel region is at an early stage, far-field WPT has been extensively studied. A comprehensive overview of the design concepts, capabilities and limitations, prototypes, and applications of WPT systems is provided in [5]–[11]. Typically, WPT systems are required to have line-of-sight (LoS) between transmitter and receiver in order to attain adequate power transfer efficiency [10]. Additionally, in state-of-the-art WPT systems, the transmit antennas of the energy transmitter are either co-located or distributed [10]. Co-located antenna architectures have been employed, for example, in [12] and distributed antenna systems (DASs) have been considered in [13], [14]. DASs are an appealing transmit antenna architecture for WPT systems and enable cooperation among the distributed transmit antennas. Compared to co-located energy transmitters, employing a DAS results in a more uniform distribution of the received power in the environment [10]. DASs for WPT have been investigated for different transmission strategies such as transmit antenna selection [14] and maximum ratio transmission [13].

In this paper, we consider a multiple-input single-output (MISO) WPT system that comprises a two-antenna energy transmitter and a single antenna energy receiver in LoS conditions. The energy receiver is located at an arbitrary position in a three-dimensional cuboid room and the transmit antennas are located on one of the room’s walls. We determine the amplitude variations of the wireless channel based on geometrical considerations and optimise the positions of the transmit antennas analytically, thereby showing whether a co-located or a distributed transmit antenna architecture is optimal. Hereby, the objective is to maximise the received power for the worst possible receiver position. Thus, the proposed solution ensures provision of the maximum, worst-case power for the given environment when there is no prior knowledge on the receiver’s location in the room. This is crucial for wirelessly powered devices utilised for continuous monitoring, such as sensors and wearables.

Our approach for optimising the transmit antenna positions of a WPT system is designed for a three-dimensional cuboid room and relies on exploiting the spherical nature of the EM wavefronts. Therefore, the existing results [5]–[14] which were obtained for WPT systems designed for the far-field operating regime are not applicable to the problem considered in this paper. The antenna placement problem is formulated.
for a general number of transmit antennas and we solve the problem optimally for a two-antenna system. The analytical expression describing the optimal transmit antenna positions only depends on the geometry of the environment. While the proposed solution is designed around capturing the effects of the spherical EM wavefronts in the Fresnel region, the solution is shown to converge to the optimal far-field solution once the distances are large enough for the PWM to become sufficiently accurate at the worst possible receiver positions. The proposed optimal transmit antenna deployment reveals that a DAS is the optimal transmit antenna architecture in the Fresnel region, whereas a co-located architecture is optimal in the far-field. The point of transition between the DAS and the co-located transmit antenna architecture is determined through geometrical considerations. Moreover, the extension of the presented methodology to systems with more than two transmit antennas is briefly discussed. The analytical solution to illuminate the entire room since the receiver may be located anywhere in the environment. The location of transmit antenna \( i \) is described by the triplet \((a_{ix}, a_{iy}, a_{iz}) \in \mathcal{X} \times \mathcal{Y} \times \mathcal{Z}, \forall i = 1, \ldots, N_t \). The amount of power obtained at the receiver is shown to depend on the placement of the transmit antennas in Subsection II-C. Consequently, the amount of power at the receiver can be maximised by optimising the positions of the transmit antennas.

There is an inherent trade-off between the achievable performance and the practicality of the transmit antenna deployment. Although leveraging the full potential of a flexible placement would yield the best performance, the resulting transmit antenna locations may be impractical or even infeasible in practice. Therefore, we restrict the antennas to being placed along a horizontal line defined by \( y = 0, z = z_0 \in \mathcal{Z} \). Consequently, the transmit antenna positions are restricted in the environment through the following condition

\[
\forall i = 1, \ldots, N_t : a_{ix} \in \mathcal{X}, a_{iy} = 0, a_{iz} = z_0 \in \mathcal{Z}. \tag{4}
\]

Throughout this paper, \( a_{ix} \) is denoted by \( a_i \) for simplicity of notation.

C. Channel and Signal Model

The Fresnel region of a wireless system is defined, e.g., in [2], and depends on the relationship between the wavelength of the EM waves and the distance between the transmit antennas in comparison to their distance from the receiver. The size of the Fresnel region increases with the carrier frequency. While the Fresnel region is negligibly small in conventional wireless systems, when using mmWave frequency bands or higher, the size of the Fresnel region becomes relevant, e.g., for indoor scenarios. Furthermore, for high carrier frequencies, the severe reflection and scattering losses cause the wireless channel to become predominantly LoS [1], [3], [15]. A LoS channel is typically assumed for wireless systems operating in the Fresnel region [2], [3], [16].

LoS between transmitter and receiver allows a WPT system to attain adequate power transfer efficiency [10]. On the other hand, we note that LoS channels are susceptible to blockages.
[3]. For analytical tractability of system design, we make the assumption that a LoS connection between the transmit antennas and the receiver exists and do not consider the impact of channel blockages in this paper.

Based on the previous considerations, free-space LoS propagation of the EM wavefronts is considered in this paper. When considering free-space LoS conditions, the equivalent complex baseband channel between transmit antenna \( i \) and the receiver is given by [17]

\[
g_i = \frac{\sqrt{c}}{D_i} e^{-j2\pi D_i / \lambda},
\]

where \( \lambda \) is the wavelength, \( D_i \) is the distance between transmit antenna \( i \) and the receiver, and \( c \) is the channel power gain at the reference distance of 1 meter. Since the wireless channel of the considered MISO system is modelled using the SWM, both the amplitude and the phase of \( g_i \) depend on distance \( D_i \).

In contrast, for the PWM, the path loss between all transmit antennas and the receiver is assumed to be constant, i.e., \( D_i \approx D, \forall i = 1 \ldots N_t \). The MISO channel is represented by the \( N_t \)-dimensional vector \( \mathbf{g} = [g_1, \ldots, g_{N_t}]^T \in \mathbb{C}^{N_t \times 1} \). The channel model in (5) has been considered for describing directional antennas and the receiver is assumed to be constant, i.e., \( \gamma \) is negligible.

Thus, the received power of the considered MISO system is modelled using the SWM, for steering beams in the far-field, it also applies to focusing energy beams towards the receiver in the Fresnel region [2]. Here, we assume the wavelength of the system is chosen such that the system is operating in the Fresnel region for a given transmit antenna placement.

By first identifying the receiver locations resulting in the worst performance independent of the transmit antenna positions, the complexity of the problem can be reduced. The set containing these critical receiver locations is denoted by \( \mathcal{X}^\text{crit} \times \mathcal{Y}^\text{crit} \times \mathcal{Z}^\text{crit} \), where \( \mathcal{X}^\text{crit} \subset \mathcal{X} \), \( \mathcal{Y}^\text{crit} \subset \mathcal{Y} \), and \( \mathcal{Z}^\text{crit} \subset \mathcal{Z} \).

**Proposition 1.** It suffices to consider the receiver locations defined by \( y = L_y \), \( z = -L_z / 2 \) and \( y = L_y \), \( z = L_z / 2 \) for optimisation problem (8), \( \mathcal{Z}^\text{crit} \) is given by \( \mathcal{Z}^\text{crit} = \{-L_z / 2\} \) if \( 0 \leq z_0 \leq L_z / 2 \) and \( \mathcal{Z}^\text{crit} = \{L_z / 2\} \) if \( -L_z / 2 \leq z_0 \leq 0 \). \( \mathcal{X}^\text{crit} \) is given by \( \mathcal{Y}^\text{crit} \) is given by \( \mathcal{Y}^\text{crit} \) is given by \( \mathcal{Y}^\text{crit} \).

Proof. The proof is based on the monotonicity of (7) in \( y \) and \( |z - z_0| \) and is given in the extended version of this paper [19]. \( \square \)

\( \mathcal{X}^\text{crit} \) cannot be obtained based on monotonicity due to the dependency between the receiver location and the transmit antenna variables in (7). Restricting the receiver positions to the critical set and defining \( L_z = L_z + 2|z_0| \), allows the following equivalent reformulation of (7)

\[
f_x(a_1, \ldots, a_{N_t}) = \sum_{i=1}^{N_t} \frac{1}{(x-a_i)^2 + y^2 + (z-z_0)^2}, \quad (9)
\]

which is independent of variables \( y \) and \( z \). Finally, (8) is equivalently reformulated as

\[
\text{maximise } \quad \min_{x} f_x(a_1, \ldots, a_{N_t}) \quad (10a)
\]

subject to \( (1), (4) \). \( (10b) \)

**III. Problem Formulation and Optimal Solution**

A. Problem Formulation

The objective is to deploy the transmit antennas such that the receiver is powered reliably anywhere in the environment. Analytically, this is attained by determining the optimal transmit antenna placement, which satisfies the constraints imposed on the positions in Section II-B, such that the received power \( \gamma \) is maximised at the worst possible receiver location. Supposing the \( i \)-th transmit antenna and the receiver are located at positions \( (a_i, 0, z_0) \) and \( (x, y, z) \), respectively, then the received power \( \gamma \), defined in (6), is proportional to the following function

\[
f_{xyz}(a_1, \ldots, a_{N_t}) = \sum_{i=1}^{N_t} \frac{1}{(x-a_i)^2 + y^2 + (z-z_0)^2}, \quad (7)
\]

which depends on the transmit antenna positions. The proposed design is obtained as the solution of the following maximin problem

\[
\text{maximise} \quad \min_{x,y,z} f_{xyz}(a_1, \ldots, a_{N_t}) \quad (8a)
\]

subject to \( (1), (2), (3), (4) \). \( (8b) \)

B. Optimal Solution

For the remainder of this paper, the number of transmit antennas is set to \( N_t = 2 \). This allows for an intuitive illustration of the geometrical considerations underlying the proposed method, thus offering insight into the solution structure of the considered transmit antenna placement problem. The application of the method presented in this paper to systems with \( N_t > 2 \) is discussed in Subsection III-D. In the following, the symmetry of \( f_x \) in (9) is investigated in Proposition 2.

**Proposition 2.** For \( N_t = 2 \), the optimal locations of the transmit antennas \( a_1 \) and \( a_2 \) must satisfy \( a_1^* = -a_2^* \).
Proof. The proof is based on ensuring the solution does not bias some receiver positions over others and is given in the extended version of this paper [19].

Proposition 2 allows dropping the dependency on $a_2$ in the objective function $f_x$, i.e., $f_x(a_1, a_2) = f_x(a_1)$, with $a_2 = -a_1$. For a given $x$, the optimal transmit antenna positions are obtained by determining the stationary points of function $f_x(a_1)$ as follows

$$
\frac{\partial f_x(a_1)}{\partial a_1} = 0.
$$

(11)

Solving (11) for $a_1$, five stationary points $a_1^\beta(x, L_y, L_x')$, $\beta \in \{I, II, III, IV, V\}$, are found and given in the following

$$
a_1^{(I)}(x, L_y, L_x') = \frac{1}{2} \sqrt{e(x, L_y, L_x') - d(x, L_y, L_x')}
$$

$$
= -a_1^{(I)}(x, L_y, L_x'),
$$

(12)

$$
a_1^{(II)}(x, L_y, L_x') = \frac{1}{2} \sqrt{-e(x, L_y, L_x') - d(x, L_y, L_x')}
$$

$$
= -a_1^{(IV)}(x, L_y, L_x'),
$$

(13)

$$
a_1^{(V)}(x, L_y, L_x') = 0,
$$

(14)

where $e(x, L_y, L_x') = 4x^2 + 4L_y^2 + L_x'^2$ and $d(x, L_y, L_x') = \left(4x^2 + 4L_y^2 + L_x'^2\right)^{\frac{1}{2}}$. Using the symmetrical relationships $e(-x, L_y, L_x') = e(x, L_y, L_x')$ and $d(-x, L_y, L_x') = d(x, L_y, L_x')$, we obtain $a_1^{(II)}(x, L_y, L_x') = a_1^{(I)}(-x, L_y, L_x')$ and $a_1^{(IV)}(x, L_y, L_x') = a_1^{(I)}(-x, L_y, L_x')$. Thus, it is sufficient to investigate the three stationary points $a_1^{(I)}(x, L_y, L_x')$, $a_1^{(II)}(x, L_y, L_x')$, and $a_1^{(V)}(x, L_y, L_x')$. Additionally, due to the symmetrical relationship between the antennas, i.e., $a_2 = -a_1$, $a_1^{(B)}(x, L_y, L_x')$ is also redundant.

Proposition 3. If the geometry of the environment satisfies $4(L_y/L_x)^2 + (L_x'/L_x)^2 \geq 3$, the optimal transmit antenna positions are $a_1^* = a_2^* = 0$, otherwise they satisfy $a_1^* = -a_2^* \neq 0$.

Proof. The proof is based on investigating when the stationary points (12)-(14) are real and is given in the extended version of this paper [19].

In summary, Proposition 3 shows that a co-located or a distributed antenna architecture is optimal depending on a linear combination of the ratios $L_y/L_x$ and $L_x'/L_x$.

Lemma 1. If the geometry of the environment satisfies $4(L_y/L_x)^2 + (L_x'/L_x)^2 \geq 3$, then $X_{\text{crit}} = \{-L_x/2, L_x/2\}$.

Proof. The proof follows from identifying the worst possible receiver locations when (12) is not real and is given in the extended version of this paper [19].

Lemma 2. If $4(L_y/L_x)^2 + (L_x'/L_x)^2 < 3$, the critical points $X_{\text{crit}}$ are either $X_{\text{crit}} = \{-L_x/2, L_x/2\}$ or $X_{\text{crit}} = \{-L_x/2, 0, L_x/2\}$. The optimal transmit antenna positions are given by

$$
a_1^* = \frac{L_x}{2} \sqrt{2 \left(4 \frac{L_y^2}{L_x^2} + \frac{L_x'^2}{L_x^2} + 1 - \left(4 \frac{L_y^2}{L_x^2} + \frac{L_x'^2}{L_x^2} + 1\right)\right)},
$$

(15)

and

$$
a_1^* = \frac{L_x}{2} \sqrt{4 \frac{L_y^2}{L_x^2} + \frac{L_x'^2}{L_x^2} + 1},
$$

(16)

in the former and the latter case, respectively.

Proof. The proof follows from identifying the worst possible receiver locations when (12) is real and is given in the extended version of this paper [19].

From Lemma 2 it follows that $a_1^*$ depends purely on the geometry of the system. Next, in Lemma 3 a condition on the geometry is established which describes the point of transition from (15) to (16).

Lemma 3. The point of transition between (15) and (16) occurs at $4(L_y/L_x)^2 + (L_x'/L_x)^2 = 5/4$.

Proof. The point of transition is identified by equating (15) and (16).

Proposition 4. The optimal transmit antenna position $a_1^*$ such that the received power $\gamma$ is maximised at the worst receiver position in the environment is given by

$$
a_1^* = \begin{cases}
0 & \text{if } 4 \frac{L_y^2}{L_x^2} + \frac{L_x'^2}{L_x^2} \leq \frac{5}{4},
\left(16\right) & \text{if } \frac{5}{4} \leq 4 \frac{L_y^2}{L_x^2} + \frac{L_x'^2}{L_x^2} \leq 3,
\left(15\right) & \text{if } 4 \frac{L_y^2}{L_x^2} + \frac{L_x'^2}{L_x^2} \geq 3.
\end{cases}
$$

(17)

Proof. The proof follows from Lemma 2, Lemma 3, and (12).

Corollary 1. The optimal transmit antenna deployment, defined in Proposition 4, yields the maximum received power $\gamma^*$ for the worst receiver position which is given by

$$
\gamma^* = PC\left\{\begin{array}{ll}
2 & \text{if } \frac{L_y^2}{L_x^2} + \frac{L_x'^2}{L_x^2} \leq \frac{5}{4},
\frac{2}{4} \frac{L_y^2}{L_x^2} + \frac{L_x'^2}{L_x^2} + 1 & \text{if } \frac{5}{4} \leq 4 \frac{L_y^2}{L_x^2} + \frac{L_x'^2}{L_x^2} \leq 3,
\frac{2}{L_y^2 + 4L_x^2 + 4L_x'^2} & \text{if } 4 \frac{L_y^2}{L_x^2} + \frac{L_x'^2}{L_x^2} \geq 3.
\end{array}\right.
$$

(18)

Proof. The proof follows from the optimal transmit antenna positions and is given in the extended version of this paper [19].

C. Power Gain over Optimal Far-Field Solution

Next, the possible power gain of employing the proposed optimal antenna positioning over the optimal far-field position is quantified. The ideal position for all transmit antennas under the far-field assumption lies in the centre of $X$. This follows from approximating the path losses corresponding to different
transmit antennas with a constant value which is analogous to the co-located transmit antenna architecture where the optimal transmit antenna positions are \( a_1^* = a_2^* = 0 \). The performance gain \( \eta \) which is obtained by designing the system using the exact SWM instead of the approximated PWM depends on the geometry of the environment. Therefore, the gain \( \eta \) is computed by comparing the performance of using the optimal transmit antenna locations in the Fresnel region (17) to the optimal ones for the far-field, which are obtained by placing both antennas at zero.

**Corollary 2.** The gain that is obtained by using the optimal transmit antenna placement depends on the geometry of the environment and is given by

\[
\eta = \begin{cases} 
\frac{12 L_z^2 + 3 L_y^2 + 3}{16 L_z^2 + 4 L_y^2 + 1} & \text{if } 4 \frac{L_z^2}{L_x^2} + \frac{L_y^2}{L_x^2} \leq \frac{5}{4}, \\
\frac{4 L_z^2 + L_y^2 + \frac{1}{2} + 4 L_z^2 + L_y^2 + 1}{16 L_z^2 + 4 L_y^2} & \text{if } \frac{5}{4} \leq 4 \frac{L_z^2}{L_x^2} + \frac{L_y^2}{L_x^2} \leq 3, \\
1 & \text{if } 4 \frac{L_z^2}{L_x^2} + \frac{L_y^2}{L_x^2} \geq 3. 
\end{cases}
\]  

(19)

**Proof.** The proof follows from the optimal transmit antenna positions and is given in the extended version of this paper [19].

**D. Systems with \( N_t > 2 \)**

The methodology outlined in this paper may be extended to systems with a larger number of transmit antennas, i.e., \( N_t > 2 \). By virtue of the max-min problem, an asymmetrical transmit antenna placement is suboptimal. Therefore, for an uneven number of transmit antennas \( N_t \), one optimal transmit antenna position must lie in the centre of \( \mathcal{X} \). Moreover, when \( N_t \) is even, Proposition 2 must hold for pairs of transmit antennas to ensure a symmetrical transmit antenna placement. The approach for identifying all critical receiver positions in \( \mathcal{X}^{\text{crit}} \) may be cumbersome for large \( N_t \), as the number of critical positions \( |\mathcal{X}^{\text{crit}}| \) is expected to grow with \( N_t \). Consequently, the number of transition points, which are necessary for formulating the optimal positions, is expected to grow. Alternatively, the optimal transmit antenna placement may then be obtained by solving (10) numerically. A numerical method of solving the problem is discussed at the end of Section IV-A.

**IV. Results and Performance Evaluation**

**A. Optimal Position of \( a_1^* \)**

The optimal position of \( a_1^* \) (17) is visualised as a function of the geometry of the system in Fig. 2. To this end, the optimal position of \( a_1^* \) is depicted as a function of one variable and one parameter. The optimal position \( a_1^* \) is given as a function of \( L_y/L_x \), i.e., \( a_1^*(L_y/L_x) \), while the value of \( L_z/L_x \) is fixed and the parameter value is indicated by the legend entry corresponding to the respective plot. The function \( a_1^*(L_y/L_x) \) is plotted by considering the parameter values \( L_z/L_x = \{0, \sqrt{3}/8, \sqrt{3}/4, 3\sqrt{3}/8, \sqrt{3}/2\} \). The parameter values are chosen to represent the boundaries of the possible geometrical ratios of the environment. For \( L_z/L_x = 0 \), the environment collapses into a two-dimensional room. The maximum value \( L_z/L_x = \sqrt{3}/2 \) follows from the condition in Lemma 3.

Fig. 2 provides insight into how the geometrical properties of the environment impact the optimal transmit antenna positions. By basing the proposed method on the SWM, an optimal solution was obtained which is capable of capturing the effects in the Fresnel region and naturally converges to the far-field solution as \( 4L_y^2/L_x^2 + L_z^2/L_x^2 \) grows. In the far-field, the impact of the spherical nature of the EM wavefronts at the worst receiver locations diminishes and the PWM becomes sufficiently accurate. Consequently, when the optimal solution for the Fresnel region coincides with the far-field solution, i.e., \( 4L_y^2/L_x^2 + L_z^2/L_x^2 \geq 3 \), then the WPT system does not have to be designed for the Fresnel region. However, for \( 4L_y^2/L_x^2 + L_z^2/L_x^2 \leq 3 \), designing the system for the Fresnel region has to be ensured, which requires considering the relationship between the wavelength and the distance between the transmit antennas in comparison to their distance from the receiver. The analytical solution was validated by solving the problem numerically. To this end, the quadratic form method in [20] for Fractional Programming was extended to max-min-ratio problems and a sequence of parameterised convex optimisation problems was solved using CVXPY [21]. The numerical results are indicated by the crosses overlaying the respective analytical results in Fig. 2. Fig. 2 also shows that the numerical method suffers from numerical inaccuracies as the optimal \( a_1^* \) approaches 0.

**B. Power Gain over Far-Field Solution**

The power gain \( \eta \) in (19) is visualised in Fig. 3 as a function of \( L_y/L_x \), while fixing the parameter \( L_z/L_x \) for every plot of the function. The values of the parameters are identical to the ones listed in Subsection IV-A. The maximum gain
is three and is achieved for $L_y/L_x \to 0$ with $L_z/\sqrt{L_x L_y} = 0$. Consequently, using the proposed optimal positioning based on the SWM provides up to three times the amount of received power compared to the far-field approach. As the impact of the spherical nature of the EM wavefronts decreases, the gain over the far-field solution drops.

V. CONCLUSION

In this paper, we considered a MISO WPT system that comprises a two-antenna energy transmitter and a single antenna energy receiver under LoS conditions. Hereby, the objective was the maximisation of the received power for the worst possible receiver position by identifying the optimal transmit antenna deployment. The approach in this paper leverages the symmetry among the positions of the transmit antennas. The symmetry is a necessary constraint in order to avoid biasing certain receiver positions over others, as this would lead to a worse objective globally. The proposed optimal, analytical solution provides insight into how the geometry impacts the optimal placement of the transmit antennas. Our solution reveals that distributing the transmit antennas in the environment is optimal when in any location of the environment the PWM is not a suitable approximation of the SWM. Otherwise, a co-located antenna architecture is optimal which corresponds to the optimal solution for the far-field. The solution was validated by solving the problem numerically. Furthermore, the maximum power gain over the far-field solution was found to be three. The extensions of the proposed solution to small-scale fading channels, multiple transmit antennas, and more flexible transmit antenna placements are interesting topics for future work.

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