Distributed Beamforming Based Wireless Power Transfer: Analysis and Realization

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Distributed Beamforming Based Wireless Power Transfer: Analysis and Realization

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Abstract: This paper presents a new Wireless Power Transfer (WPT) approach by aligning the phases of a group of spatially distributed Radio Frequency (RF) transmitters (TX) at the target receiver (RX) device. Our approach can transfer energy over tens of meters and even to targets blocked by obstacles. Compared to popular beamforming based WPTs, our approach leads to a drastically different energy density distribution: the energy density at the target receiver is much higher than the energy density at other locations. Due to this unique energy distribution pattern, our approach offers a safer WPT solution, which can be potentially scaled up to ship a higher level of energy over longer distances. Specifically, we model the energy density distribution and prove that our proposed system can create a high energy peak exactly at the target receiver. Then we conduct detailed simulation studies to investigate how the actual energy distribution is impacted by various important system parameters, including number/topology of transmitters, transmitter antenna directionality, the distance between receiver and transmitters, and environmental multipath. Finally, we build an actual prototype with 17 N210 and 4 B210 Universal Software Radio Peripheral (USRP) nodes, through which we validate the salient features and performance promises of the proposed system.

Key words: Wireless Power Transfer (WPT); distributed beamforming; wireless network

1 Introduction

Ever since the invention of electricity, a world free of batteries and power cords has been the aspiration of many scientific investigations. Now, this vision is ever more appealing, with the proliferation of Internet of Things (IoT) systems, and at the same time ever more realistic thanks to recent advances in low-power design and energy harvesting. As an example of low power IoT devices, in the year of 2016, Graule et al.[1] made a robotic drone that only needs 19 MW to fly, and a couple of micro watts to remain perched on objects. Such extremely low power devices can be potentially powered through simple mechanisms such as ambient energy harvesting. For example, the EnHANTs system leverages ambient lights as energy resources, and enables communication and networking among active embedded nodes[2]; in Ref. [3], low power IoT devices are powered by a Wi-Fi router; and the Ambient Backscatter system[4] harvests energy from TV and cellular signals in the surrounding, realizing ubiquitous communication among devices.

While ambient energy harvesting has proved effective in the above examples, it becomes less effective in many other situations, especially when the required energy
density exceeds what the environment offers. For such scenarios, the idea of wirelessly shipping power to the target has been explored at different times in history—earliest by Tesla back in 1904\[^5\], and later in 1965 by Brown\[^6\] who transferred hundreds of watts to power an unmanned helicopter by making a highly directional antenna and efficient energy harvester. Recently, several wireless energy delivery technologies have been developed. Disney research introduces the Quasistatic Cavity Resonance (QSCR), which enables purposefully built structures, such as cabinets, rooms, and warehouses, to generate quasistatic magnetic fields that deliver kilowatts of power to potentially inductive receivers\[^7\]. The MagMIMO system\[^8\] leverages the concept of closed loop beamforming in the manner of multiple magnet coils array, transferring significant amount of energy into a cellphone at arbitrary locations within 40 cm from the source magnet coil array. MagMIMO also tracks the receiver by utilizing feedback from the receiver, eliminating the requirement that one must place the receiver at certain locations in traditional magnet coil based systems. However, these approaches have practical concerns, which we illustrate in Fig. 1a—as people endeavor to deliver higher amount of energy over longer distances, it is hard to strike the balance between delivering high energy level at target location and lowering energy density at other non-target locations because many wireless transfer systems incur higher energy on the transmitter-receiver path than at the target.

In this study, we design and build a distributed beamforming based Wireless Power Transfer (WPT) approach that can (1) deliver energy over tens of meters and (2) have the maximum energy level at the target location. Such an approach can potentially lead to safe and practical wireless charging solutions by controlling the power level at the target within a safe range, we can ensure that the power level at other locations is also safe. Also, due to its distributed nature, our approach can efficiently transfer energy even when there are human subjects or other large obstacles in the space; while in a traditional beamforming based WPT system, having obstacles on the beam may significantly undermine the energy transfer efficiency.

Towards this goal, we arrange our distributed transmitters in a fully distributed fashion by surrounding them around the target receiver, as shown in Fig. 1b. We draw inspiration from the design of the surround sound system, in which multiple speakers are arranged around the audience for better audio experiences. A salient property of this arrangement is that, by aligning their phases at the receiver, the energy level at the target receiver is higher than the energy level at any other spot in the charging area. In fact, a small energy ball is formed around the receiver. Figure 1b shows the energy density distribution of our system using simulation results.

Our approaches come from the inspiration of Fresnel zone plates focus light\[^9\]. In our design, in a manner analogous to creating a Fresnel zone plate, we discretize the zone plates into multiple independent phase shifters. Each phase shifter is a far-field Radio Frequency (RF) transmitter in our system. We establish a constructive superposition of these far-field emitters at the target receiver. From simulations, by increasing the number of RF emitters, we find that we could focus the energy to desired locations. In the implementation, we place 24 transmitters at four corners of our 20 m × 20 m testbed, acting as a zone plate. The result is, by making all transmitters constructively interfere at the receiver, we transfer considerably high energy to the target receiver in precision. To prove the effectiveness, we measure that the resultant energy distribution pattern in our proposed proof-of-concept system is very similar to simulation results.

In summary, our work has the following contributions:

1. We propose a distributed beamforming based wireless power transfer approach, that can establish a
desirable energy density distribution with a high target to average energy ratio with the peak resided in the receiver location. To transfer the same amount of energy to a device, such a system leads to much less RF energy in the charging area than traditional beamforming systems.

- We mathematically model the spatial energy distribution for our proposed system. We prove the received power at the target receiver is higher than at all other locations. We find our proposed system can deliver a comparable amount of energy to any location in the charging space even with multipath or obstacles (human subjects and/or other large objects) in the space. We also build a real world prototype using 21 Universal Software Radio Peripherals (USRPs) to validate these properties of our system.

- We propose three metrics to evaluate our system: overheating ratio, 3 dB energy ball width, and target to average energy ratio. A good WPT system should have the overheating ratio equal to zero, a small 3 dB energy ball width, and a high target to average energy ratio. Through detailed simulations, we study the impact of many important system parameters on the system performance, including system operating radio wavelength, phase alignment error from transmitters, number of transmitters, directionality of transmitter antennas, transmitter deployment, multipath effect, and different transmitters to receiver geometries.

Our paper is organized as follows. We first discuss our related work in Section 2. Next, in Section 3, we present the design details of our system, from its intuition to analytic modeling and proof of its properties. Next, in Section 4, we extensively study system performances using simulations. Then we describe how we build an actual system using USRPs and evaluate our proposed system in Section 5. Lastly, conclusion of this paper is given in Section 6.

2 Related Work

2.1 Electromagnetic radiation based energy harvesting and transferring

Near-field inductive coupling exploits magnetic field induction effect to deliver energy between two coils\cite{10}. Research works in this domain focus on inductive power link optimization\cite{10-13}, source-load decoupling\cite{14}, and multi-coil linkage design\cite{8,15}. While near-field method achieves satisfying power delivery efficiency, it requires the target receiver device to be close to coils and align them with the receiver coil\cite{16}. As a result, the target needs to placed still for hours to be fully charged. Moreover, the charging efficiency of near-field methods drops significantly with the reduction of coil size, which limits their working range to less than a centimeter\cite{17,18}. Hence, the focus in this field has shifted towards overcoming the coil misalignment problem and improving the system robustness.

Far-field wireless charging transfers power to the target through electromagnetic radiation\cite{19-21}, microwave radiation\cite{22}, or laser\cite{23,24}. Compared to the near-field method, the far-field method supports wireless charging over a longer distance at the cost of lower wireless charging efficiency. Research in this field focuses on RF diode and DC impedance optimization\cite{19}, antenna optimization\cite{20}, and effective system implementation\cite{21}. IVN\cite{25} introduces an opportunistic frequency-encoding method in hope of combining signals constructively at the medical implant. However, IVN’s beamforming power, for most of the time, is far below the maximum value it can potentially achieve.

We take the viewpoint that far-field active transferring is the most promising approach to enabling a large array of beamforming-IoT systems with diversity charging energy and distance requirements. In this paper, we propose a new WPT approach that leverages a group of transmitter antennas to increase the delivered energy. Our approach is however drastically different from beamforming based WPTs in that it arranges the transmitter antennas in a completely different manner and thus yields completely different energy density distribution in the charging area. In the next subsection, we will then take a close look at the energy density distribution of these two types of WPT approaches.

2.2 WPT energy density distributions and their implications on safety

The risks of excessive RF energy exposure have been studied in the past, which have revealed that harmful biological effects may stem from strong RF radiation\cite{26-31}. High energy density across the charging space in WPT systems may cause excessive RF energy exposure, which we strive to avoid in the design of our system.

Existing beamforming based WPTs have unwanted RF energy exposure along the beam. Due to path loss, the energy density on the beam path is higher than that at the target receiver. Specifically, the simulation results in Fig. 1a show that on the beam path, the energy density at 1 m away from the transmitter array is 13 times higher than the energy density at the target.
receiver. If the beamforming system is designed with only the received energy in mind, without realizing that the energy level on the path may become much higher, then it is hard to guarantee that the energy density on the beam is low enough to meet the Federal Communications Commission (FCC) regulations or to be safe. FCC establishes different exposure limits for different RF ranges. These limits are codified in Title 47 of the Code of Federal Regulations (CFR). Specifically, as for conventional far field wireless charging frequency of 915 MHz, Maximum Permissible Exposure (MPE) for uncontrolled environment is 0.6 MW/cm² [32]. In addition, due to skin depth effect [33], WPT systems operating at higher frequencies naturally interact more strongly with the human body than lower frequency WPTs [34].

Clearly, guaranteeing safety is one of the key objectives when designing a wireless charging system, especially those that can work over several meters or longer [35]. A safe WPT approach has been investigated in Ref. [36]. In this work, under the MPE constraint, the proposed approach selects specific energy chargers for a given set of available energy chargers. On the other hand, a laser based wireless power transfer approach is proposed in Ref. [23], where it automatically detects people in its laser beam path and turns the laser beam off. In our system, as shown in Fig. 1b, the peak energy exists precisely at the target receiver. Thus, by controlling the energy level at the receiver at a safe level, the entire charging area should also be safe.

3 Distributed Beamforming Based Wireless Energy Transfer

3.1 Overview

Our proposed WPT approach has two main components. Firstly, we arrange a set of distributed transmitters around the target receiver (we will discuss the spatial relationship between transmitters and receiver later in Section 4.3), and secondly we align their phases at the receiver.

In free space, the received signal’s magnitude \( R(t) \) and power \( P \) are

\[
R(t) = e^{j\omega t} \sum_{i=1}^{N} a_i / d_i e^{j(\beta_i + \phi_i)}
\]

\[
P = \left| \sum_{i=1}^{N} a_i / d_i e^{j(\beta_i + \phi_i)} \right|^2,
\]

respectively, here \( a_i \) is the amplitude of the \( i \)-th transmitter, \( d_i \) is the distance between this transmitter and the receiver, and \( \beta_i = (d_i / c) + \theta_i \) is its initial phase, which is random and unknown to the system. Usually \( \phi_i \) serves as our steering phase and is controllable. Received power \( P \) is maximized when all transmitters are properly phase aligned, i.e., \( \beta_1 + \phi_1 = \cdots = \beta_i + \phi_i = \cdots = \beta_n + \phi_n \). We adjust each transmitter’s \( \phi_i \) to reach phase alignment. Here, even though the transmitters may not have built-in synchronization/communication mechanisms among them, we will show that it is feasible to successfully align their phases at any receiver location.

Figure 2a shows the energy density distribution of our proposed system from a Matlab simulation. In this simulation, we place 100 transmitters in free space on a circle, with the radius of 10 m, and place the receiver at the center of the circle. The energy density distribution shows that once the transmitter phases align at the receiver, the energy density at the receiver location is the maximum across all the points in the area. Specifically, the target to average energy ratio in this area is 72.6. Further, if we look at a location that is only 5 cm away from the receiver location, its Receive Signal...
Strength (RSS) is only 10% of the peak RSS value. Figures 2b and 2c compare the histograms of received power (normalized) for our proposed system and a traditional beamforming WPT system that described in Fig. 1. We clearly see that, for our proposed system, the target receiver has the maximum received power across the measured area. On the other hand, in traditional beamforming based WPT system, the received power for the target receiver is far less than the maximum power, and there are a lot other locations have received power higher than the target receiver. In order to differentiate this type of distributed beamforming from traditional beamforming, such as those in Refs. [37, 38], we refer to it as energy-ball forming. That is, an energy ball is formed around the receiver whose energy is highest in the entire space.

Due to the nature of our approach, we believe it is of great potential, likely leading to safe and practical WPT solutions.

3.2 Modeling the energy density distribution

To understand the radio focusing effect of our system, suppose we place $N$ transmitters on a circle with radius $R$ in free space around the receiver (located at the center of the circle), and they coherently combine their phases at the receiver. Assuming, without loss of generality, that they align their phases at 0 degree at the center, then the normalized RSS at the receiver is given by

$$Y_{\text{target}} = \left| \frac{R}{N} \sum_{i=1}^{N} \frac{1}{R} e^{j0} \right| = 1$$  \hspace{1cm} (1)

Next, we want to measure the normalized RSS at a non-focus point that is distance $d$ away from the focus, as shown in Fig. 3a. Considering an arbitrary transmitter and the free space model, the phase difference $\Delta \phi$ between the focus location and measurement location is

$$\Delta \phi = 2\pi \frac{\sqrt{R^2 + d^2 - 2Rd \cos \varphi} - R}{\lambda} \hspace{1cm} (2)$$

where $\lambda$ is the wavelength of operation radio, $\varphi$ is shown in Fig. 3a.

Suppose we approach an infinite amount of transmitters (placed on the circle), we can write the normalized RSS at the measurement location as

$$Y(d) = \left| \lim_{N \to \infty} \frac{R}{N} \sum_{i=1}^{N} \frac{1}{d} e^{j2\pi \frac{\sqrt{R^2 + d^2 - 2Rd \cos \varphi} - R}{\lambda}} \right| = \frac{R}{2\pi} \int_{0}^{\varphi} e^{j2\pi \frac{\sqrt{R^2 + d^2 - 2Rd \cos \varphi} - R}{\lambda}} d\varphi, \varphi \in [0, 2\pi] \hspace{1cm} (3)$$

Figure 3b shows the analytical result of $Y(d)$ in Eq. (3), and Fig. 3c shows the simulation result, both
assuming transmitters emitting RF signals of 3 GHz. In the simulation, we considered 100 transmitters. Note that these two results are nearly identical, therefore validating our analysis. Further, we can see in Fig. 3d that the results for the normalized RSS expression $Y(d)$ has a spatial pattern similar to the magnitude of a sinc function, with the maximum at the target receiver location. This location corresponds to where transmitter signals coherently combine (phases aligned).

**Maximum RSS level at the target location.** Next, we prove that in the free space, $Y(0) > Y(d)$ when $d > 0$; i.e., the RSS at the focal point is higher than the RSS value at any other location. We take a close look at $Y(d)$ in Eq. (3). Considering the symmetry of transmitters placement with respect to the focal point, we can ignore the path loss term $1/d$ in our analysis:

$$\frac{1}{2\pi} \int_{0}^{2\pi} \exp\left[\frac{R^2 + d^2 - 2Rd \cos \varphi}{\lambda} \right] d\varphi = \lim_{N \to \infty} \frac{1}{N} \sum_{i=1}^{N} \exp\left[\frac{R^2 - R^2 \cos \varphi_i - R^2}{\lambda} \right], \quad \varphi_i \in [0, 2\pi]$$

Hence, the only maximum of this summation is reached when the phase of each term aligns with each other, i.e., $Y(0)$ is the unique global maximum. In other words, when transmitters align their phases at a certain location, the RSS at this location is higher than the RSS at other locations.

**Phase error tolerance.** We assume we have perfect phase alignment in our previous study. However perfect phase alignment is difficult to realize in practice due to (1) clock drifting among transmitters, (2) environmental variations, and (3) measurement errors in the phase alignment process.

Interestingly, there is a relative large phase error tolerance for the distributed phase alignment. Figure 4 shows a simulation result for the phase error tolerance. There are 100 transmitters in this simulation, we investigate the received power at the target receiver (peak power) with each transmitter has 0–360 degrees of phase errors. This result shows the target receiver can still receive over 80% of optimal power even if each transmitter has around 50 degrees of phase error. The reason is, in our system design, transmitters deliver RF energy using narrow band sinusoid signal, and derivatives around the optimal region of sinusoid signal are relative low.

**3 dB energy ball width.** Considering an asymptotically large number of transmitters in Eq. (3), we have verified that the distance between the point that receives the maximum energy level and the first point that receives half of the maximum energy, which is usually called 3 dB-down distance ($d_{3\text{dB}}$) in communication, is

$$d_{3\text{dB}} \approx 0.22\lambda$$

We can use $d_{3\text{dB}}$ to represent the size of the energy ball, which is proportional to the RF wavelength we use for charging. For an operating frequency of 1 GHz, $d_{3\text{dB}}$ is around 13 cm, which is quite focused. Further, through simulation studies, we find that even for a smaller number of transmitters or asymmetric transmitter placement, $d_{3\text{dB}}$ would still be a fraction of $\lambda$ as long as transmitters are placed around the target receiver.

4 Detailed Study of the Energy Ball Performance

We have proved that with an infinite number of transmitters in the free space, we achieve the maximum power level at the target location. This unique energy density distribution is important for realizing safe WPT. In this section, we conduct detailed simulations to study in realistic settings, how the actual energy density distribution is affected by a number of important system parameters, including the number/placement of transmitters, parameters of transmitters, relative distance between transmitters and receiver, and environmental factors such as wireless multipath parameters.

**4.1 Performance metrics**

In the following discussion, we call the area surrounded by the transmitters as transmitter area. In order to better
describe the energy density distribution of our proposed system, we study the following four performance metrics: (1) overheat ratio, (2) target to average energy ratio, (3) 3 dB energy ball width, and (4) energy delivery efficiency.

**Overheat ratio.** In realistic settings, the received power at the target location might not be the maximum received power across the entire space. We refer to those locations that receive higher power than the target receiver as overheat locations. As shown in Fig. 5, we measure the received power from 10,000 locations that are uniformly sampled from a cubic space, which we refer to as measurement space. The overheat ratio is defined as the number of overheat locations divided by 10,000 measurement locations. Given a specific transmitter number and placement, the received power level within the measurement space is higher than the power level outside of the measurement space, except those locations that are very close to individual transmitters. When a location is less than \( d_f = 2D^2/\lambda \) away from the transmitter (\( D \) is the effective radius of TX area, and \( \lambda \) is the radio wavelength), the energy distribution cannot be described using the far field model, and thus not considered here. We ensure that every point in the measurement space falls in the far field of all the transmitters.

**Target to average energy ratio.** We refer to the received power at the target receiver as target power, and the target to average energy ratio is this target power over the average received power of the 10,000 measured locations within the measurement cube.

**3 dB energy ball width.** As we discussed in Section 3.2. We use 3 dB energy ball width as another metric to study the tightness of energy ball. Instead of having infinite number of transmitters placed on a circle, in this section, we study how the 3 dB ball width changes in different transmitter/receiver deployments given the number of transmitters.

**Energy transfer efficiency.** The end-to-end energy transfer efficiency is the ratio between the received power amount and the total transmitted power amount (\( p_{rx}/\sum p_{tx} \)). Given the energy transfer efficiency, number of transmitters, and output power for each transmitter, the received power at the target receiver can be conveniently calculated.

Since our transmitters work in far-field settings, the end-to-end energy transferring efficiency is rather low. However, it is the physical limitation of any far-field WPT system. The end-to-end efficiency could be increased by using directional transmitters. We argue that such an energy delivery system is still valuable, mainly because the value of transmitted power and the value of received power are often asymmetric, especially if the receiving node is in a hard-to-access region. As IoT devices are made increasingly low-power, this concern becomes less severe.

### 4.2 Impact of transmitter parameters

#### Number of transmitters. In practice, deploying a large number of transmitters is not only prohibitively expensive, but also not practical as it will be hard to achieve synchronization/phase alignment among them. We will then study the system performances when we have different numbers of transmitters.

Figures 6a–6d show overheat ratios, target to average energy ratios, 3 dB energy ball widths, and efficiency in different numbers of transmitters. In these simulations, transmitters are still placed on a circle (\( r = 10 \text{ m} \)) centered around the receiver. The overheat ratio decreases to 0 while there are more than 11 transmitters, the target to average energy ratio is quasi-linear to the number of transmitters, the 3 dB energy ball width stays 2.6 cm after there are more than 9 transmitters, and the efficiency is not sensitive to the number of transmitters. Moreover, we look at some specific cases, Figs. 7a–7d show simulation results of the detailed energy density distribution around the target receiver (within a \( 10 \text{ m} \times 10 \text{ m} \) area) with different transmitter numbers. The results show that when the number of transmitters exceeds a certain threshold (8 in our case), the energy level at the receiver is the highest. The target to average ratio goes up when we increase the transmitter number. Specifically, when we have 8, 16, 25, and 50 transmitters, the target to average energy ratio is 6.1, 11.3, 21.2, and 41.4, respectively.
Fig. 6  Impact of transmitter number. We show (a) overheat ratios, (b) target to average energy ratios, (c) 3 dB energy ball widths, and (d) efficiency when we vary the number of transmitters. Transmitters are placed along a 10 m radius circle centered at the receiver.

Fig. 7  Detailed energy density distribution in a 10 m × 10 m area centered at the receiver for four specific settings: (a) 8 transmitters, (b) 16 transmitters, (c) 25 transmitters, and (d) 50 transmitters. The red x marks the received power at the target receiver.

In practice, we built an actual testbed consisting of 24 transmitters, and we will show later in Section 5.3.2 that the energy at the receiver is indeed considerably higher than any other spot.

**Directional transmitters.** We assume the energy transmitters are isotropic in our previous analysis. Directional energy chargers are often used in WPT system for boosting the charging efficiency. The bar plots in Figs. 8a–8d show overheat ratios, target to average energy ratios, 3 dB energy ball widths, and efficiency with different antenna directionalities. We observe that the overheat ratio stays zero with different directionalities, the higher antenna directionality can largely increase the overall target to average energy ratio and efficiency, and more interestingly, the higher antenna directionality significantly decreases the 3 dB energy ball width. However, using directional transmitters brings complexity in real world system implementation. We have to steer the orientation of each directional transmitter such that it aims at the target receiver. This is part of our future work on this topic.

Further, in order to show the advantage of directional transmitters more straightforward, in Fig. 9, we use simulations to compare the detailed energy distributions in the following two cases: (1) when we use a 10 dB directional antenna for each transmitter (radiation patterns of directional antennas that we use are in Ref. [39]) and (2) when we have isotropic transmitters. In both cases, there are 100 transmitters that are deployed along a circle of the same radius and the receiver is placed at the center of the circle. We observe that the target to average energy ratio is 228.5 using
target to average energy ratio without increasing overheat locations. It can also shorten the 3 dB energy ball width. As a result, it can facilitate the possibility of charging more power-hungry IoT nodes, such as drones or robots.

4.3 Impact of transmitter and receiver placement

Different transmitter placements. Next we investigate how different transmitter deployments impact on energy density distribution. Figures 10a and 10b show different views of the energy distribution when we place 100 transmitters along a circle, i.e., the views on the $x$-$y$ and $y$-$z$ planes ($x$-$z$ view is the same as the $y$-$z$ view due to symmetry). Note transmitters are placed on the $x$-$y$ plane. The receiver is placed at the center of the transmitter area. Interestingly, we observe a high energy line in the $y$-$z$ and $x$-$z$ planes. This is due to the fully symmetric placement of the circular transmitter area. As shown in Fig. 10c, we form an energy-cylinder while the receiver is placed at the center of this circular transmitter area. Specifically, the 3 dB ball width is 2.6 cm in the $x$-$y$ plane, but the 3 dB ball width goes to 127 m in the $y$-$z$ and $x$-$z$ planes.

On the other hand, in Figs. 11a and 11b, we show different views of the energy distribution when we place 100 transmitters along a rectangle. The receiver is also placed at the center of the transmitter area. In the simulation, a high energy ellipsoid-energy-ball is formed around the target location (shown in Fig. 11c). Similar
as the circular transmitter placement, the rectangular transmitter placement can still achieve high target to average energy ratio (69.7) while it does not form an energy-cylinder if the receiver is placed at the center. This is better since the 3 dB ball width is 0.9 m in the y-z and x-z planes while the 3 dB ball width is still 2.6 cm in the x-y plane.

Further, through more simulations, we have studied different transmitter geometries, and found that asymmetric transmitter deployments are usually better, but arrange transmitters on a sphere leads to the narrowest energy focus around the receiver. It suggests that three-dimensional transmitter deployments (not necessarily symmetric) are over two-dimensional deployments.

Impact of receiver placement. We have shown one can form a tight energy ball around the target receiver when placing the target receiver at the geometric center of the transmitters. We next investigate the impact of receiver placement using simulations. We first look at the simulation results—we place 100 transmitters that are equally spaced along a $r = 10 \text{ m}$ circle, we show overheat ratios, target to average energy ratios, energy ball 3 dB distances, and efficiency when we place the receiver from 0 to 1000 m (Figs. 12a–12d) and 0 to 30 m (Figs. 12e–12h from the center of transmitter area). As can be seen, the overheat ratio becomes larger than 0 while the receiver is placed more than 70 m away, the target to average energy ratio increases at first but then decreases after the receiver goes outside of the transmitter area. More interestingly, the target to average energy ratio is still high when the receiver is placed within a small region (less than 20 m) outside of the transmitter area. The 3 dB distance is relative stable and small when the receiver is placed within the transmitter area, the 3 dB distance starts increasing when the receiver is placed further away from the transmitter area. Moreover, Figs. 12d and 12h show the end to end energy delivery efficiency when the receiver is placed at different distances to the transmitter area. An interesting observation we have is that, within the transmitter area, the target energy level received at each location varies from point to point. The results suggest that the target energy level actually increases as the receiver location moves away from the center (until the receiver reaches the edge of the transmitter area). This shows that if possible, we can change the receiver’s location within the transmitter area to receive relative large amount of energy. We further validate these results using real world measurements in Section 5.3.3.

Next, we look at several specific cases—we consider 100 transmitters that are equally spaced along a $25 \text{ m} \times 25 \text{ m}$ square, place the receiver at four different locations, and show the detailed energy distribution within a $10 \text{ m} \times 10 \text{ m}$ area around the receiver in Figs. 13a–13d. In Fig. 13a, the receiver is placed at the center of the transmitter area. In Fig. 13b, the receiver is placed within the transmitter area, but not at the center. In Fig. 13c, the receiver is placed outside of the transmitter area, but its distance to the square is comparable to the length of

![Fig. 12](image_url) Impact of the distance between the transmitter area center and the receiver. We show (a) overheat ratios, (b) target to average energy ratios, (c) 3 dB energy ball widths, and (d) efficiency when we vary this distance from 0 to 1000 m. Further, we show the zoomed-in view of (e) overheat ratios, (f) target to average energy ratios, (g) 3 dB energy ball widths, and (h) efficiency when we vary this distance from 0 to 30 m. We have 100 transmitters that are placed along a 10 m radius circle.
Fig. 13  Detailed energy density distribution in a 10 m × 10 m area centered at the receiver for four specific transmitter-receiver placement settings: (a) receiver placed at the center of transmitter area; (b) receiver placed in the transmitter area, but not the center; (c) receiver placed outside of transmitter area, but close; (d) receiver placed further away to the transmitter area. The red × marks the received power at the target receiver.

the side (its distance to the center of transmitter area is 85 m). In Fig. 13d, the receiver is placed far away from the transmitter area (its distance to the transmitter area is 200 m). We find that the energy density distribution in Fig. 13d approaches traditional beamforming system.

We take the viewpoint that our system differs from traditional beamforming systems because it yields very low overheat ratio. For example, if we would like to keep the overheat ratio below a small number, say 0.5%, then the receiver needs to be within 130 m away from the transmitter area center, which is 13 times of the transmitter area radius. This result suggests that, not only do we not need to place the receiver exactly at the center, but we do not need to keep the receiver too close to the transmitter area as well. As a result, the deployment of our WPT system is rather flexible in terms of the distance between the charging target and the transmitters.

4.4 Impact of deployment environment

In our earlier studies, we assumed the free space model, we next show that our proposed system can successfully focus on RF energy and charge devices even when there are complex multipaths or obstacles in the charging area. We refer these features as ubiquitous charging. To simulate the multipath effect, we next use a statistical model, Gaussian Wide Sense Stationary Uncorrelated Scattering (GWSSUS)\cite{40} to model the channel condition. GWSSUS assumes that all the scatterers form clusters, and are distributed uniformly between and around transmitter and receiver. As a result, we have Rician distribution when Line of Sight (LoS) rays exist, and Rayleigh distribution in non-LoS cases. Also, the phase of each path is uniformly distributed in the interval of \([0, 2\pi]\). However, due to the closed loop nature of our phase alignment algorithm\cite{41, 42}, the feedback from the receiver already takes multipaths into account. Hence, transmitter phases are still aligned by following the receiver’s feedback, and the RSS at the target receiver is the sum of the RSS values from all possible paths.

Figures 14a–14d show overheat ratios, target to average energy ratios, 3 dB energy ball widths, and efficiency when we simulate different numbers of multipaths for each transmitter. Higher number of multipaths indicates more complex RF environments. This result shows that the overheat ratio is always 0, around 40 target to average energy ratio can be achieved even if there are 25 multipaths for each transmitter, 3 dB energy ball widths slightly vary with different multipath settings, and the variations of efficiency under different multipaths are similar as target to average energy ratios. As such, our system works in complex multipaths environments. Further, we look at a specific case, Fig. 15a shows the detailed energy distribution

![Fig. 14 Impact of multipath effect. We show (a) overheat ratios, (b) target to average energy ratios, (c) 3 dB energy ball widths, and (d) efficiency when we vary the number of multipaths for each transmitter. 100 transmitters are placed along a 10 m radius circle centered at the receiver.](image-url)
Fig. 15 Detailed energy density distribution in a 10 m x 10 m area centered at the receiver for (a) shows the detailed energy density distribution simulation result under GWSSUS channel and (b) shows the detailed energy density distribution simulation result in free space. The red x marks the received power at the target receiver.

simulation result using the GWSSUS channel model with 100 transmitters placed on a circle. We assume each transmitter has 3 paths (1 LoS + 2 non-LoS paths). As we can see, there is still a focused high energy spot around the target receiver, while the energy density becomes rather random in other locations. The target energy in this case is 86.3% of the target energy in the free space case. The target to average energy ratio in free space (with the same setup, shown in Fig. 15b) is 72.6, while the target to average energy ratio in this multipath scenario is 62.1, which we believe can still lead to safe charging.

More importantly, the fact that our system works well in multipath environments makes it less influenced by obstacles that are presented between transmitters and target. In fact, having obstacles randomly placed in the space has very similar effect as having uniformly distributed clusters between and around transmitter and receiver in GWSSUS multipath channel assumptions, which only marginally affects the energy level at the target receiver. This salient merit stems from our system does not have a primary line of sight energy delivery path, and blocking all charging paths is merely possible. Our measurement results presented in Section 5.3.3 again confirm that the RSS at the receiver does not change much when we arranged multiple people randomly standing at different locations between transmitters and the receiver.

5 Real World Testbed Implementation and Evaluation Using USRPs

In order to implement and evaluate the system design presented in Sections 3 and 4, we develop an actual testbed consisting of 17 N210 and 4 B210 USRP nodes.

5.1 Testbed setup

We deploy 17 USRP N210 and four USRP B210 software defined radios on the ceiling of an office building, as illustrated in Fig. 16. Each USRP is equipped with a WBX RF daughter board\[43\] and works on FDD full duplex mode. We use a Mini Circuits ZFL1000VH RF amplifier\[44\] to boost the signal power and send out the amplified signal through a 4 dBi Taoglas TG.35.8113 antenna\[45\]. As USRP only supports relative signal power measurement\[46\], we conduct a one-time power calibration using an Agilent E4405B spectrum analyzer\[47\] to acquire the absolute signal power.

USRPs synchronization. To mitigate the clock drift and Carrier Frequency Offset (CFO), all USRPs are wired to an Octoclock-G GPS Disciplined Oscillator (GPSDO)\[48\] with 10 MHz reference signal. This
centralized time synchronization method provides an accurate timing reference. Wireless-based time synchronization methods such as Refs. [49, 50] can be further employed for an even larger system deployment.

5.2 GNU radio implementation

Signal processing overview. Signal processing tasks are performed by the GNU radio version 3.7.6.1. An overview of implementation flow for transmitters and the receiver is illustrated in Fig. 17. We write multiple out-of-tree GNU radio modules to implement our functions.

5.3 Evaluation

Using the USRP-based testbed, we have conducted thorough and carefully designed experiments to evaluate the proposed merits of our system.

5.3.1 Convergence of feedback control phase alignment method

We first evaluate the performances of phase combining algorithm by measuring the convergence time.

Experimental setup. Figure 18a shows a successful coherent phase combining. As soon as feedback control phase alignment starts running, the signal magnitude continues to increase until it stabilizes around the maximum value, at which point we say the system has converged, or has achieved a successful phase combining. In order to report the average convergence time of feedback control phase method, we need to measure the convergence time under different settings, i.e., different initial phases for transmitters. Towards this objective, we design the following experimentation plan. Figure 18a illustrates an example topology, in which we have 2 receivers, RX\_1 and RX\_2. Before an experiment starts, both receivers do not send feedback messages, and therefore, the transmitters just emit signals without the attempt of combining them. We first turn on the feedback from RX\_1 and make the transmitters combine their phases around it. After we detect the system has converged, we turn off the feedback from RX\_1 and turn on that from RX\_2. As a response, the transmitters start combining their phases at RX\_2, and meanwhile the phases of incoming signals at RX\_1 become uncoordinated and drift to random values. We repeatedly alternate between these two receivers. In this way, we could measure the system convergence time when transmitters employ different initial phases.

Result. Here, we compare the convergence times when we use feedback control phase alignment with \( N = 1 \) (1 random phase adjustment in each round) and feedback control phase alignment with \( N = 2 \) (2 random phase adjustments in each round). We vary the number of transmitters to be 2, 4, 7, 10, and 12, and conduct a total of 150 experiments. The results in Fig. 18a show that feedback control phase alignment with \( N = 2 \) can converge significantly faster than feedback control phase alignment with \( N = 1 \), reducing the convergence time by as much as 30%.

![Fig. 17 TX and RX signal processing flow in our system.](image)

![Fig. 18 (a) Performance of 1 random adjustment feedback control phase alignment and 2 random adjustments feedback control phase alignment with different numbers of transmitters. (b) Using the topology shown in Fig. 16b, we measure the power level distribution of our system in a 6 m x 6 m area centered at the receiver. (b) presents the 3D view of distribution, while (c) presents the histogram of the power level measurements. The distribution clearly shows that the energy density level at the receiver (marked by the red x) is much higher than that at other spots within the measurement area.](image)
In the rest of the evaluation section, we will use feedback control phase alignment with \( N = 2 \).

**5.3.2 Energy density distribution of our system**

Next, we measure the energy density distribution in the charging area. We show that with our system, the energy level at the target receiver is the maximum across the entire area. We have also implemented a traditional beamforming based WPT system and compare its energy distribution pattern with our system.

**Experimental setup.** We use the topology shown in Fig. 16b for our system implementation in this experiment. On the other hand, for comparison, as shown in Fig. 19a, we build a beamforming rack which has 16 transmitting antennas and 16 receiving antennas to perform MRC\(^{[51]}\) beamforming based WPT.

The main challenge in conducting this experiment is measuring the energy distribution in the area. Manually sampling the area would take a significant amount of time (e.g., tens of hours), and it is very hard to keep the radio environment around the receiver stable within this period. Performing parallel measurements with multiple USRPs is not a viable approach either, due to differences in their hardware.

We thus use a specifically designed robot\(^{[52]}\) to address this challenge. The receiver’s antenna is attached onto the robot. In this method, as soon as the phase combining at the receiver stabilizes, we stop the receiver from sending feedback messages. As a result, the locked phases at the transmitters lead to coherent phase combining at the original receiver’s location. Next, the robot will traverse the intended scanning area by a preset trace, which will cover the intended area as much as possible. Meanwhile, the receiving USRP is recording the RSS during the whole process, and the RSS values are eventually mapped to their corresponding locations by comparing the timing information of the robot and the receiving USRP.

During our experiment, we also make sure that the observed RSS\(_{\text{combined}}\) value at the energy delivery destination (the original receiver location) does not have noticeable variation.

**Results.** In our topology (shown in Fig. 16b), we have measured a 6 m \( \times \) 6 m (this size is limited by the maximum length of the coax cable) rectangular area around the receiver. Figure 18b shows the measured received power distribution in a 3D view. We clearly witness a sharp energy peak around the target receiver location, while the energy at other locations are very low. Figure 18c shows the statistics of measured received power from the robot: the received power at target receiver is 0.63 MW, which is the maximum received power of all measured spots. 62\% of measured received power is less than 0.063 MW and 99\% of measured received power is less than 0.31 MW.

As far as the MRC beamforming based WPT is concerned, Fig. 19b shows the measured received power distribution. A strong energy beam projects toward the target receiver, and most of the received powers (89\% of measured locations on the line of main beam) on this beam are higher than the received power at the target receiver. Figure 19c shows its statistics: received power at target receiver is 0.54 MW, but there are 8\% of measured spots that have received power higher than the target receiver.

We note that on our facility, we cannot move these USRP antennas around, and as a result, the distances between the transmitters and the receiver in these two systems are different. Because of this, it is hard for us to directly compare the delivered power amount in both systems, nor can we compare their charging efficiency. However, we do see that these two systems lead to very different energy density distribution patterns. Our

![Fig. 19](image-url)
system has the energy peak only at the target receiver. Specifically, the target to average received power ratio in this experiment is 8.72. As we noted in Section 2.2, these patterns potentially have different implications on safety of the system especially when the delivered energy amount goes up.

5.3.3 Ubiquitous charging

Another important benefit from our system design is the ubiquitous charging, that is, we are going to show our system can deliver substantial energy to different target receiver locations and make sure if there are people blocking in the charging space.

(1) Energy delivery at any point across the room.

We have built a 20 m $\times$ 20 m area testbed. We now show our system can align phases and delivery energy at any point within this area. For this purpose, we place the target receiver at 42 different locations, measure the delivered energy at each spot, and show the results in Fig. 20a. Among these 42 locations, location 1 is the center of the charging area while the other 41 locations are randomly chosen. Specifically, the received power at location 1 is 0.57 MW. When we move the receiver to a different location, our system re-align transmitters’ phases. Experiment results show they all converge to over 90% of the optimal received power. Among these 42 measurements, the minimum, average and maximum received power are 0.51 MW, 0.63 MW and 0.74 MW, respectively.

(2) Energy delivery in the presence of obstacle blocking.

Experimental setup. We have different amounts of people randomly changing their locations in our 20 m $\times$ 20 m testbed. During the whole experiment, our system is running and keep adapting transmitters phases according to the environment dynamic. There are 1, 2, 3, 4, and 5 people in each test, and these testers as asked to randomly change their position 30 times in each test. For comparison purpose, we also recorded 30 RSS data while no people in the tested space.

Result. Figure 20b shows the measured received power statistics with different numbers of blocking objects. It shows the blockage makes minimum influence on the optimal charging power. We even notice the power can go higher than no blockage. The result indicates our system’s charging is nonsensitive to blockage. The ubiquitous charging property is a pronounced merit over traditional point to point charging system.

6 Conclusion

In this paper, we present a new WPT approach that transfers wireless energy to intended receivers by arranging a group of distributed transmitters around the receiver and coherently combining their phases at the receiver. This approach is a departure from existing beamforming based WPT approaches which have high energy on the energy beam path. The key innovation of our approach is that it can maximize the received power at the receiver, and have a low overheat ratio, a high target to average energy ratio, and a narrow 3 dB energy ball width. Through detailed modeling and simulations, we show that the proposed approach can maximize the power level at the target receiver, and the energy delivery is not sensitive to obstacles blocking, and show system performances in different system parameter settings. Finally, we evaluate our proposed WPT system using 21 USRP nodes across a 20 m $\times$ 20 m area.

![Fig. 20](image-url) (a) In our 20 m $\times$ 20 m test area, we place the receiver at 42 locations, in which location 1 is the center of the area and the other 41 locations are randomly chosen. We show the received power at each of these receiver locations here. Results show the received power at most of the locations is higher than the received power level at the center of the deployment area (location 1). (b) Box plot of the received power statistics for different numbers of blocking subjects. Our proposed system can deliver comparable or even higher energy to the target receiver with people blockage.
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