Study of Distributed Beamforming for Wireless Power Transfer in the Presence of RF Impairments

Florin Huţu, Vincent Lechappé, Guillaume Villemaud, and Michaël Di Loreto

Abstract – For equivalent performance (sensitivity, communication range, computational capability, etc.), the energy efficiency of connected devices is continuously increasing. Providing the energy for such objects by means of electromagnetic waves (wireless power transfer) becomes a feasible option in various scenarios, especially those in which the use of conventional energy resources (e.g., batteries) is unfeasible. This article tackles a particular method of wireless power transfer: distributed beamforming—i.e., the use of several spatially distributed sources coordinating to maximize the power of the electromagnetic field in a particular location. Through simulation results, this article highlights the robustness of this approach to different nonidealities—frequency and phase synthesis, phase noise, and channel characteristics. A first experimental setup is also presented.

1. Introduction

All studies have predicted an exponential increase in the number of connected devices (50 billion in 2020 [1]) in a multitude of applications, including agriculture, industry, and health monitoring. This huge number of connected devices gives an idea of how important is to find new ways to decrease their environmental impact.

In many Internet of Things applications, the use of classical energy sources is inappropriate; one example is sensors buried in concrete monitoring mechanical efforts inside walls. The sensor life span will be strictly related to the battery life span. For these scenarios, the solution of transmitting all or some of the energy through electromagnetic waves may be considered. Indeed, this solution is feasible because of the increasing efficiency of electronic devices. Some studies (e.g., [2]) predict that in the next decade, the energy needed for a computational task will decrease by a factor of 10 000 compared to current levels.

Wireless power transfer has already been proposed as a method to energize connected devices. Generally, research focuses on the receiver side to increase the efficiency of the RF power rectifier, since this is the main limitation. Efficiency varies with respect to the received input power. To the best of our knowledge, to have a rectifier efficiency greater than 25% with current technology, the received signal should be superior to –20 dBm [3].

In order to increase rectifier efficiency, some recent works have focused on the use of multicarrier signals [4]. Indeed, such signals are renowned for having a high peak-to-average power ratio and for increasing the DC voltage level at rectifier output [5]. Some other works propose a systemic view of maximizing the efficiency of wireless power transfer by taking into account the power source, the effects of the propagation channel, and the characteristics of the rectifier [6].

Wireless power transfer using time-reversal technology was proposed in [7]. This technique is based on a spatiotemporal focusing effect. After a channel probe, made by sending an impulse signal, the transceiver returns a time-reversed, conjugate, and amplified replica of the received impulse. These replicas combine at the exact spot of the initial pulse, creating a relatively high amount of electromagnetic field energy there.

Distributed beamforming has already been proposed as a way to maximize wireless power transfer, and some theoretical solutions have been proposed [8]. Here they formulate the problem of maximizing the power delivered by a distributed antenna array to a receiver by taking into account the channel effects. A fixed-point algorithm gives the optimum power allocations in a finite set of frequencies.

In distributed beamforming, a network of individual wireless nodes with single antennas cooperate to generate synchronized signals. The considered sources may be access points in wireless local area networks or cellular base stations. The initial phase of the emitted signals is chosen in such a way that phase coherence occurs at a desired spot. Consequently, the amplitude of the electromagnetic field is locally maximized. The main contribution of this article is to study the impact of RF impairments on the amount of energy transferred by distributed beamforming. More precisely, taking an ideal scenario as reference, we study the power decrease in the presence of frequency and phase-synthesis errors, source phase noise, and a realistic propagation channel.

In Section 2, distributed beamforming for wireless power transfer is formalized, and some simulation results tackle the impact of different beamforming synthesis errors on the received power level. Section 3 presents an experimental setup built to validate the

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Florin Huţu and Guillaume Villemaud are with Université de Lyon, INSA (Institut National des Sciences Appliquées) Lyon, Inria, CITI (Center of Innovation in Telecommunications and Integration of service), F-69621, Villeurbanne, France; e-mail: florin-doru.hutu@insa-lyon.fr, guillaume.villemaud@insa-lyon.fr.

Vincent Lechappé and Michaël Di Loreto are with Université de Lyon, Université Claude Bernard Lyon 1, CNRS (Centre National de la Recherche Scientifique), Ampère, F-69622, Villeurbanne, France; e-mail: vincent.lechappe@insa-lyon.fr, michael.di-loreto@insa-lyon.fr.

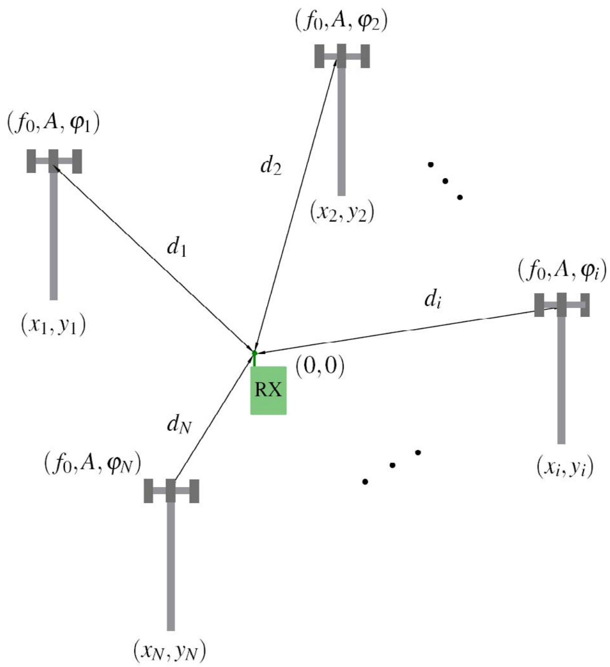

Figure 1. Scenario of wireless power transfer using geographically distributed RF sources.

distributed beamforming scenarios. The conclusion and future directions are given in Section 4.

2. Problem Statement and Simulation Results

Consider N identical sources randomly distributed in a Cartesian plane as in Figure 1. These sources coordinate to obtain phase-coherent signals at the origin of the coordinate plane in order to perform wireless power transfer efficiently. Each source is defined by its coordinates (x_i, y_i), where $i \in [1, N]$. Each source is able to generate a signal at a frequency f_0 and with an identical power level P. At the center of the coordinate system is a receiver with low energy resources.

This receiver is supplied power by the electromagnetic field produced by the N sources. As stated, the power of the received electromagnetic field is maximized if the arriving signals are in phase coherence. In order to obtain phase coherence at the receiver level, the initial phase of the emitted signals should be

$$\varphi_i = \frac{2\pi}{\lambda_0}\sqrt{x_i^2 + y_i^2} \quad (1)$$

where λ_0 is the wavelength of the emitted waveform.

In the case of phase coherence, the power level collected by the receiver increases with the number of sources. In the particular case in which N sources are placed at the same distance around the receiver, the gain related to the power level received from one source can be expressed as

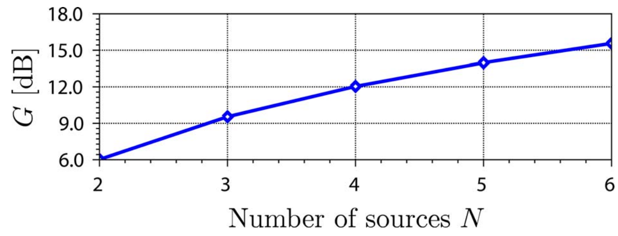

Figure 2. Gain in terms of received power.

$$[G]_{\text{dB}} = 20\log_{10}(N) \quad (2)$$

Indeed, suppose that only one source is emitting. The received power level can be written as

$$[P_R]_{\text{dBm}} = 10\log_{10}\left(\frac{A^2}{R}\right) \quad (3)$$

where A is the amplitude of the received sinusoidal waveform and R is the load presented by the receiver.

Consider now that all N sources are emitting sinusoidal waveforms at the same frequency, so that the signals arrive in phase coherence at the receiver level. In this case, the received power level becomes

$$[P_{RN}]_{\text{dBm}} = 10\log_{10}\left[\frac{(NA)^2}{R}\right] \quad (4)$$

If the gain in terms of power G is defined as

$$G \triangleq \frac{P_{RN}}{P_R} \quad (5)$$

then the result given in (2) is straightforward. As an example, from Figure 2, which is the graphical representation of (2), one can remark that when four sources are emitting, the gain in terms of received power is 12 dB.

In order to verify this theoretical gain in a more realistic scenario, a simulator based on Keysight's ADS software was implemented. In this simulator, each source is placed at a certain distance from the sink and is able to deliver a continuous-wave signal. Between the different sources and the sink, a free-space path-loss propagation channel was considered as a first step.

If the scenario given in Table 1 is simulated, the received signals have an identical phase of 150.8° and the received power level is –33.04 dBm. In this particular case, the emitted power levels are –20 dBm and antenna gains are 4.1 dBi. Cables connecting

Table 1. Coordinates and initial phases of the continuous-wave sources

Antenna	x (m)	y (m)	φ (°)
1	−0.75	0.6	0
2	0.75	0.7	68.2
3	−0.65	−0.75	33.4
4	0.85	−0.85	−108.2

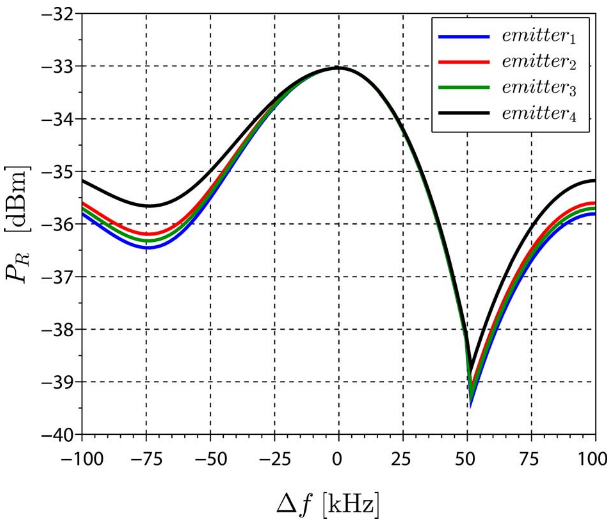

Figure 3. Variation in received power level with respect to the central frequency offset.

different antennas with an insertion loss of 0.85 dB were also taken into account.

Moreover, the simulator is able to test the effect on the received power of frequency and phase-synthesis deviation. Figure 3 presents the variation of the received power level if one of the emitters among the four has a frequency deviation Δ_{f} with respect to the central frequency $f_0 = 868$ MHz. As can be seen, compared to the maximum power level (–33 dBm), the received power level is about 1 dB lower for deviations of the emitted frequency around ± 25 kHz from the ideal value. This value corresponds to a variation of the synthesized frequency of approximately 28.8 ppm (parts per million) and shows the sensitivity of the distributed beamforming strategy to frequency variations.

Figure 4 presents the impact of phase deviation on the received power level. More precisely, the phase of one emitter is modified with respect to the desired value, while the other three phases remain at their ideal values. The received power level is insensitive to the phase synthesis, since power diminutions of 1 dB are obtained for errors $\Delta\varphi$ greater than $\pm 60°$ with respect to the ideal phase φ_{i}.

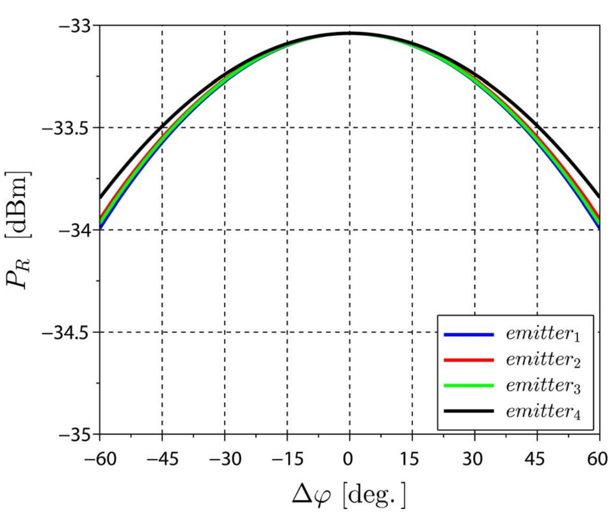

Figure 4. Variation in received power level with respect to the deviation of the desired phases φ_{i}.

These simulation results show the consequence of the synchronization between different sources, which seems to be more important than that of phase synthesis.

Another parameter which was suspected to have an influence on the distributed beamforming accuracy was the local oscillator's phase noise. Indeed, real oscillators present random variations of their instantaneous phase which may corrupt the phase accuracy at the receiver side. In order to test this influence, the phase noise of the National Instruments PXIe-5644R RF vector signal transceiver (VST) was considered as reference. This transceiver has good performance in terms of phase noise, and it is expected that the different sources used for distributed beamforming will present poor performance. The VST's phase noise levels are given in Table 2.

Table 2. National Instruments PXIe-5644R vector signal transceiver phase noise

Parameter	Value				
Frequency (kHz)	10^{-1}	10^{0}	10^{1}	10^{2}	10^{3}
P_{N} (dBc/Hz)	−83	−101	−104	−115	−143

Figure 5 presents the variation of the received power level when the phase noise floor is increased with respect to the values given in Table 2. A parametric simulation was performed, increasing the power level of the phase noise by a quantity P_{N}. All four sources are considered to have identical phase noise levels. As can be seen, a phase noise of –38 dBc/Hz at 100 Hz will decrease the received power level by 1 dB compared to the ideal value. The local oscillator's phase noise has a small impact on the accuracy of the distributed beamforming performance, since this value is beyond the ones announced for most of the commercial radio front ends. Moreover, this result reinforces the remark that distributed beamforming is robust in terms of phase synthesis.

The propagation channel also plays an important role in the accuracy of the phase coherence at the receiver side. In a realistic distributed-beamforming

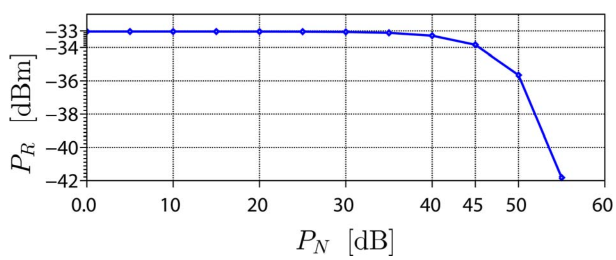

Figure 5. Variation in received power with respect to the increase of the phase noise level.

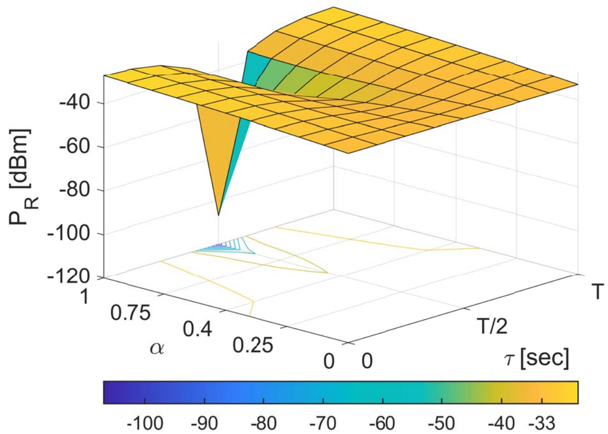

Figure 6. Influence of the propagation channel on the received power level.

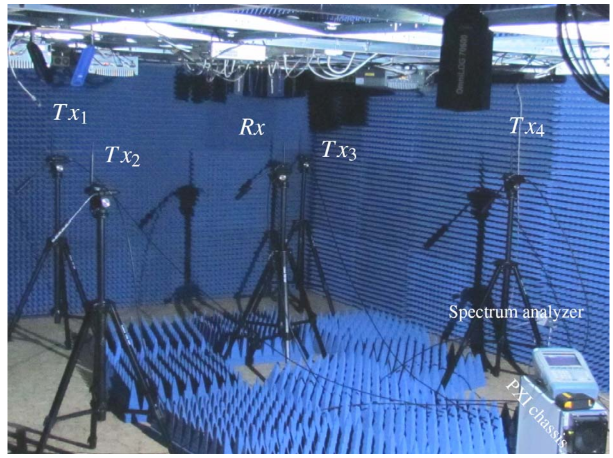

Figure 7. Measurement setup deployed in a quasi-anechoic chamber.

scenario, multipath phenomena between the emitters and the receiver are unavoidable. Propagation channels with multiple paths (Rice channels) were considered between each emitter and the receiver.

The Rician factor $\alpha \in [0, \ldots, 1]$ was considered as in [9], being the ratio between the amplitude of the line-of-sight (LOS) power level and the power of the non-LOS (NLOS) version. The NLOS path was considered to be delayed by a factor $\tau \in [0, \ldots, T]$, where $T = 1/f_0$ is the period of the emitted signals.

As can be remarked from Figure 6, a multipath channel decreases the received power level only if the NLOS version of the emitted signal is closed to quadrature (i.e., $\tau \approx T/2$). This degradation is more important when the Rician factor α is high (i.e., the power level of the NLOS received signal is close to the LOS power level).

3. Experimental Setup

A distributed-beamforming scenario was implemented in an FIT/CorteXlab test bed [10], a quasi-anechoic environment. A National Instruments PXI chassis containing four 5645 VSTs is the core of the experimental setup. The four VSTs were used as continuous-wave generators, and a spectrum analyzer was used to measure the received power level.

Experiments were conducted at 868 MHz. As can be seen from Figure 7, four omnidirectional antennas have been connected to the VSTs' RF output. The antennas have a gain of 4.1 dBi, the coaxial cables have the same phase shift at 868 MHz, and the emitted power level was set to –20 dBm for each of the four VSTs. One receiving omnidirectional antenna has been placed at the center of a Cartesian coordinate system. The synchronization of the four VSTs and their phase coherence were tested beforehand.

More precisely, the phase coherence was assured by sharing the local oscillator of one of the VSTs to the other three. A calibration procedure was implemented to cancel the phase offset brought by the coaxial cables connecting the VTSs' local oscillators' inputs and outputs.

The scenario presented in Table 1 was implemented for a received power level of approximately –34.5 dBm, close to the simulated one. The difference between the simulated and measured received powers may come from the antenna-gain uncertainty.

4. Conclusion

This article presented distributed beamforming as a solution for wireless power transfer. The impact of RF-chain nonidealities on the received power level was also addressed. Moreover, the article presented an experimental setup able to implement distributed-beamforming scenarios. Future work will focus on implementation of algorithms that are able to take into account the impact of the propagation channel, since it is the most unpredictable part of the distributed-beamforming setup.

5. Acknowledgment

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6. References

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