RF Wireless Power Transfer: A Study on the Power Transfer Efficiency of Different Waveforms and an Overview of the Standardization Efforts

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***Abstract*—The number of wireless communication devices is drastically increasing every year, reaching more than 24 billion in 2030. While the communication capabilities of these devices are continuously developing, the methodologies used for powering them are still conventional. To maintain their energy needs, the devices typically need to be either 1) regularly plugged in with a cable for recharging, 2) their batteries need to be replaced, or 3) they need to be manually placed on top of a wireless magnetic charging pad. All three powering methods require regular manual maintenance, which can be costly for applications with large number of devices, or even impossible when the devices are hard to locate or access. Radio Frequency (RF) signals, conventionally used only to transfer data, can be used also to transfer energy over the air. To harvest this energy, a device needs to convert the RF signal to a direct-current (DC) signal to power its circuitry. RF energy can be sufficient for powering low-power devices.**

In this paper, we experimentally show the effect of the transmit signal waveform on the amount of DC power harvested by an energy harvesting receiver. In particular, we use a signal generator from Rohde & Schwarz that transfers RF signals to power a battery-less receiver from Powercast. The flexibility of the signal generator enabled transmitting different waveforms, showing that transmit signals with high peak-to-average power ratio, e.g. a 5G orthogonal frequency division multiplexing (OFDM) signal, can deliver higher DC power to the receiver compared to a constant-envelope sinusoidal signal with the same average transmit power. Moreover, we discuss the standardization efforts made by AirFuel Alliance to bring the RF wireless powering technology to the market by ensuring interoperability of different manufacturers incorporating this technology. In addition, we give an overview of a 3GPP study on ambient IoT as a use case for the RF wireless power transfer technology.

***Index Terms*—Wireless power transfer, RF energy harvesting**

I. INTRODUCTION

Wireless powering is an enabling technology for many applications that include large number of low-power devices and/or battery-less devices. For example, consider powering thousands of wireless sensors in smart buildings, sensors distributed in autonomous vehicles, electronic shelf labels used for pricing each product in a store, inventory tags attached to goods to track them in warehouses, or low-power Internet of things (IoT) devices used in production lines, industrial IoT, and retail. In all these use cases, the devices are typically large in number and low in power needs.

While Barcode and RFID technologies, used e.g. in asset identification, have ultra-low complexity and small form factor, they only work in limited reading range and typically require handheld scanning, which is labor intensive and time consuming. Moreover, RFID lacks interference management schemes, especially in dense deployments. Hence, RFIDs cannot support large scale networks with seamless coverage.

One way to wirelessly power devices is using magnetic induction. However, this technology works only in a mm to cm range, requires stringent alignment between charger and receiver, requires bulky coils in devices, and requires manual charging, which is not practical for large-scale IoT applications. Renewable energy sources such as solar/wind energy may also be used to power IoT devices. However, these sources are weather dependent and work only outdoors. On the other hand, radio frequency (RF) signals can transfer energy over several meters distance, without orientation restrictions, on demand, indoors, and independent of weather conditions. With RF signals, low-power IoT devices can be powered, while in use, and while in motion, and most importantly, without the need of manual intervention, making RF energy a maintenance-free energy source. This property of RF signals attracted significant research interest in the past decade. A receiver can be powered by RF signals through a rectenna, which is an antenna followed by a rectifier. The antenna captures the RF signal and the rectifier converts the RF signal to a direct current (DC) signal. This DC energy can then be used to directly power the device or can be stored in a storage element, such as a battery or a super capacitor, for future use.

The rectifier typically contains diodes followed by a capacitor-based low-pass filter (LPF), making it a non-linear circuit element. Hence, the DC power out of the rectifier depends non-linearly on its RF input power. Owing to the rectifier's nonlinearity, its output DC power depends not only on the strength of the input RF signal, but also on its waveform [1]–[4]. For example, experiments have shown that signals with high peak-to-average power ratio (PAPR) yield higher harvested DC power for a given average incident RF power compared to constant-envelope signals [1]. This is because, the peaks of a high-PAPR signal are more likely to exceed the turn-on voltage of the diode compared to a constant envelope signal with the same average power but lower peak power. Moreover, the peaks of a high PAPR signal can charge the capacitor to a high voltage level, and if the output LPF has a large time constant, the capacitor can maintain the charged

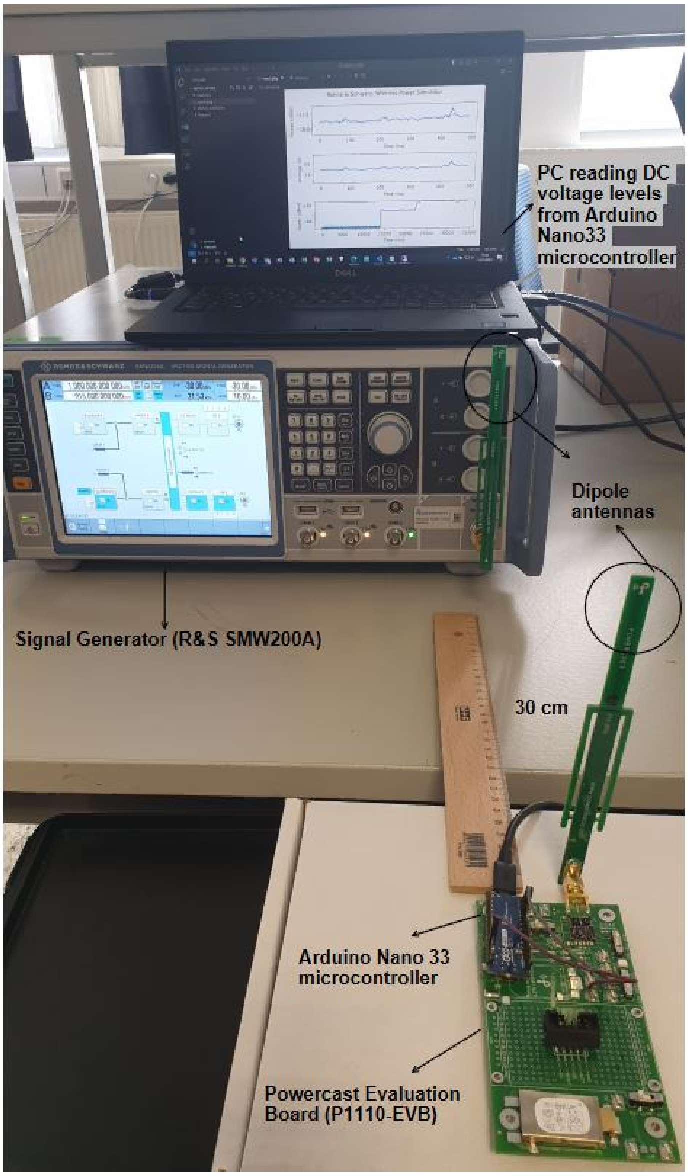

Fig. 1: Setup showing RF wireless power transfer of a sinusoidal waveform and an OFDM waveform with an average transmit power of 10 dBm at 915 MHz center frequency. Using the signal generator R&S SMW200A as the transmitter and the Powercast evaluation board P1110-EVB as the RF-to-DC conversion receiver, RF power is transferred over a 30-cm distance. The DC output voltage of the receiver is measured by the microcontroller Arduino Nano 33 and displayed as a trace on a PC.

high-voltage level until the next signal peak, resulting in a high output DC voltage, see e.g. [1, Figure 9].

II. EXPERIMENT

TABLE I: Experiment Devices

Device function	Device used
Signal generator	R&S SMW200A vector signal generator
Batteryless Receiver	P1110 Evaluation Board(P1110-EVB)
Antenna	Dipole antenna (DA-915-01)
DC power measurement unit	Arduino Nano 33 IoT

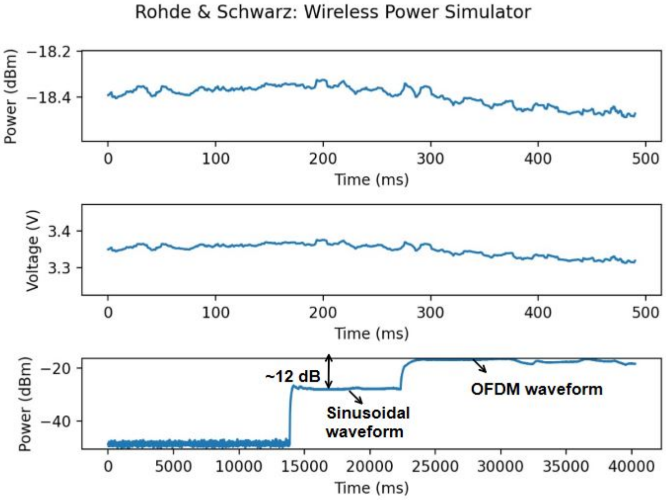

Fig. 2: A trace of the DC voltage and power at the output of the receiver Powercast evaluation board as read by the microcontroller. Top trace is the DC power in a 0.5 s span. Middle trace is the DC voltage in a 0.5 s span. Bottom trace is the DC power in a 40 s span, showing a 12 dB gain of power using OFDM waveform compared to sinusoidal waveform.

In this paper, we use the setup shown in Fig. 1 and present the effect of the PAPR of the RF signal on the rectified DC power out of an RF energy harvesting receiver. In particular, we use the devices listed in TABLE I. The signal generator, R&S SMW200A, acts as the RF signal source, that is capable of generating RF signals of different waveforms. Here, sinusoidal signals and 5G OFDM signals are used, as an example of a constant-envelope signal and a high PAPR signal, respectively. Both waveforms are transmitted with an average power of 10 dBm and a center frequency of 915 MHz, which is the same operating frequency of the receiver (the ISM band). The energy harvesting receiver ”P1110 Powercast Evaluation Board” is used to capture the RF signal by a dipole antenna and convert it to DC. In addition, we use the microcontroller unit (MCU), Arduino Nano 33 IoT, as a DC power measurement unit. In particular, the MCU is attached to the receiver and is connected to the DC voltage out pin of the receiver. The measured DC voltage by the MCU is then read by a PC and displayed in a trace curve, shown in Fig. 2.

In Fig. 2, the two upper curves show the latest 0.5 s trace of the DC power and the DC voltage at the receiver output, respectively. The output DC power, P_{DC}, is calculated from the DC voltage, V_{DC}, measured by the MCU, using $P_{\mathrm{DC}} = V_{\mathrm{DC}}^2/R$, where $R = 775k\Omega$ is the output resistance of the energy harvesting receiver circuit, measured from the output voltage pin to the ground. The bottom curve in Fig. 2 shows the DC power in a longer trace of 40 s displaying a longer history of the DC level. As shown by the bottom curve, in the first 14 s, the transmitter is turned off. Afterwards, a sinusoidal constant-envelop waveform is transmitted with an average power of 10 dBm leading to a DC power of -30.6 dBm at the receiver. Then, a 5G NR OFDM signal is transmitted with the same 10 dBm average power leading to a DC power of -18.4 dBm at the receiver. The high PAPR of the OFDM signal resulted in approximately 12 dB gain in the DC power at the receiver. This confirms the advantage of using high PAPR signals for RF wireless power transfer, showing that just by shaping the signal to have high PAPR improves the harvested DC power at the receiver, without increasing the transmitted RF power at the transmitter. Hence, high PAPR signals improve the wireless power transfer efficiency.

III. AIRFUEL ALLIANCE RF STANDARD

In order for a wireless transmitter from one vendor to be able to wirelessly power a receiver from another vendor, there must be a standard that defines all procedures between the transmitter and the receiver for them to be interoperable. Unlike proprietary solutions, having a global standard promotes the development of products employing wireless powering. To this end, Airfuel Alliance defined a standard for RF wireless power transfer. In particular, AirFuel Alliance is a global coalition of companies developing standards for both near-field (using magnetic resonance) and far field (using RF signals) wireless powering technologies. AirFuel Resonant standard is already adopted by commercial devices. The AirFuel RF baseline system specification was recently published in January 2023. The AirFuel RF interoperability and conformance tests are in the publication process. For a device to be certified by the AirFuel Alliance RF standard, it needs to satisfy these test cases. These standardization efforts aim to make wireless charging with RF signals as ubiquitous as WiFi for communications.

IV. AMBIENT IOT IN 3GPP

The 3rd Generation Partnership Project (3GPP) is a global organization defining standards for telecommunications, such as 3G to 5G communication standards. 3GPP addressed the IoT market needs with low power wide area (LPWA) technologies, such as Long-Term Evolution Machine Type Communication (LTE-MTC) and Narrowband-IoT (NB-IoT). The LPWA technologies consider stringent requirements on the size, complexity, and power consumption of the communicating device. Yet these technologies do not cover cases, where regular manual battery replacement or recharging are unsafe for devices placed in hazardous environments, highly costly for thousands of devices, or not applicable for devices placed in unknown locations. Moreover, new IoT applications include batteryless devices, i.e., devices with no energy storage capability that completely depend on the availability of an external source of energy.

Therefore 3GPP studies these new requirements with a new technology category named "Ambient IoT" with requirements and use cases defined in TR 22.840 and Air Interface defined in TR 38.848. The number of connections and/or device density in an Ambient IoT network can be orders of magnitude higher than existing 3GPP IoT technologies. Also Ambient IoT devices' complexity, energy storage capacity, power consumption ($< 10\,\mathrm{mW}$), and network coverage are orders-of-magnitude lower than existing 3GPP LPWA technologies. The low-power needs of Ambient IoT devices makes RF signals a promising energy source, capable of powering them on demand. The 3GPP Ambient IoT in Release 19 covers

- Usecases: include sensing, positioning, and inventory in indoor, outdoor, or mixed environments.
- Connectivity Topologies: include direct communication of Ambient IoT and base station or having intermediate nodes. Also direct communication of an Ambient IoT device with a user equipment (UE) is addressed.
- Spectrum: Communication in licensed spectrum in-band/guard-band/standalone of NR spectrum.
- Energy sources: RF, solar/light, electromagnetic, electrostatic, heat/thermal, thermoelectric, magnetic, wind/water, acoustic, piezoelectric (kinetic/vibration), etc.
- Coverage: ranges between 10 m and 50 m for indoor and 50 m to 100 m for outdoor.
- Device type: Ambient IoT devices are characterized according to their energy storage capacity and their capability of generating RF signals for their transmissions. Three device types are defined
  - Device A: No energy storage, no independent signal generation, i.e. backscattering transmission.
  - Device B: Has energy storage, no independent signal generation, i.e. backscattering. Use of stored energy can include amplification for reflected signals.
  - Device C: Has energy storage and independent signal generation, i.e., active RF transmitter components.

V. CONCLUSION

In this paper, we experimentally showed that high PAPR RF signals can transfer wireless power more efficiently compared to constant-envelop signals. We also summarized standardization efforts for RF wireless power transfer by the AirFuel Alliance. In addition, we addressed the new 3GPP technology "Ambient IoT" that covers usecases whose power consumption, complexity, and energy storage capabilities are orders of magnitudes lower than existing 3GPP IoT technologies. RF energy is a promising energy source for these usecases.

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