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# Experimental Assessment of Electromagnetic Fields Inside a Vehicle for Different Wireless Communication Scenarios: A New Alternative Source of Energy

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**Abstract:** The search for new energy sources in the 21st century is a crucial topic with an essential economic and societal meaning. Today, energy from electromagnetic fields (EMFs) is considered a promising new energy source for ultra-low-power consumption devices, such as wearable devices and Internet of Things (IoT) sensors. The research goal of this study was to experimentally evaluate the electric field (E-field) inside a compact car for several realistic wireless communication scenarios and to explore the possibility of using these EMFs in energy-harvesting applications. For each scenario, we performed measurements of E-fields in an urban area, in two cases: when the car was in an open space without a direct line of sight to a base station, and when the car was in underground parking. The results show that the highest measured value of the electric field appeared during the voice calls via the GSM network. Moreover, the maximum measured values of the electric field during a UMTS, LTE and 5G voice call were five to six times lower than those in the GSM network.

**Keywords:** new energy sources; electromagnetic fields (EMFs) energy harvesting; IoT devices; Wireless Sensor Networks (WSNs)



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## 1. Introduction

The search for new energy sources in the 21st century is a crucial topic with essential economic and societal meaning. Energy from renewable sources has been considered an additional form of energy that has the potential to provide energy services without increasing environmental pollution (i.e., energy services with zero or near-zero emissions) [1]. Solar and wind energy are the most widely used renewable energy sources in the world today [2]. Their share in the global electricity mix exceeded 10% in 2021 [3]. Moreover, the rapid development of fifth-generation (5G) cellular networks and the Internet of Things (IoT) requires new energy sources (other than solar and wind energy) to power small autonomous IoT devices. IoT devices are battery-powered heterogeneous (in both functionality and appearance) devices that find applications in various fields, from healthcare to applications in industry and advertising [4,5]. It is expected that the number of IoT devices will reach 29 billion in 2030 [6]. The growing proliferation of wireless IoT devices over the next few years will lead to an increase in energy consumption on the one hand and more batteries produced on the other hand, a situation that can create a significant environmental problem [7]. Hence, the question of how to provide a sustainable energy supply to IoT devices is becoming an increasingly important issue for the success of next-generation IoT networks. Energy from electromagnetic fields (EMFs) is considered a promising new energy source for ultra-low-power consumption IoT devices, such as wearable devices and IoT sensors [7–14]. Radiofrequency (RF) energy harvesting, which is the conversion of energy from EMFs emitted from devices in wireless cellular networks (2G, 3G, 4G and

5G) and local networks (IEEE 802.11) into usable electrical energy, has several advantages compared to the rest of the resources [15]. First, in urban and rural areas, RF energy is present for twenty-four hours, and second, this energy is independent of environmental conditions (such as temperature and weather conditions).

One key parameter when designing an energy harvesting system for low-power IoT devices is the achievement of maximum conversion efficiency [16]. The maximum energy conversion efficiency mostly depends on the incident power density on the antenna elements of the energy harvesting system, i.e., from available RF energy in the environment [17]. Moreover, available RF energy in the environment depends on the frequency, time of day and location. Consequently, it is essential to measure EMFs in practical cases in different scenarios, for example, in dense urban areas, urban areas and suburban areas, as well as in closed spaces [18].

EMF measurements have been carried out in various environments, such as dense urban areas [17,18] and urban and suburban areas [19–21]. Only several studies have evaluated EMFs within a closed space, such as an empty vehicle cabin [22,23]. The results reported in [23] showed that measured values for E-fields are higher in a compact-type car compared to those of a sedan-type car. Moreover, [22,23] addressed non-realistic scenarios without any car drivers or passengers. We found only one study [24] that provided measurement results of E-fields from real mobile phones during an ongoing call (GSM mode) inside a car cabin. We could not find studies on the evaluation of EMFs from mobile phones providing LTE or 5G wireless connections in a vehicle cabin. Hence, this paper concentrates on the experimental assessment of the E-field inside a compact car for several realistic wireless communication scenarios, such as GSM, LTE, UMTS and 5G ongoing calls (voice mode), as well as GSM, LTE, UMTS and 5G wireless data transmissions (data mode), to explore the possibility of using these EMFs in energy-harvesting applications. For each scenario, we performed more than 1600 measurements of E-fields in an urban area in two cases: when the car was in an open space without a direct line of sight to a base station, and when the car was in underground parking. This paper's content is organized as follows: Section 2 presents a brief literature review regarding main concepts such as RF energy harvesting, IoT devices and Wireless Sensor Network (WSN) usage in the modern economy. This part also stresses the potential usage of energy harvesting from EMFs as a future solution for the optimization of the usage of IoT devices and WSNs. Section 3 describes the measurement equipment, methodology, measurement procedure and scenarios. Section 4 highlights the main results of the experiment and proposes a discussion around the potential usage of RF energy harvested from a controlled environment, such as a vehicle's interior. Results from the experiment confirmed the hypothesis that the EMFs emitted by wireless devices in a car can be used as a new energy source to power battery-less wearable or IoT devices, and they can be used to design energy harvesting systems with maximum conversion efficiency. Section 5 presents the main conclusions along with the research limitations and future directions of research, also stressing the value of the present research before the previous literature in the field.

## 2. Brief Literature Review on RF Energy Harvesting and Its Importance for IoT Devices and Wireless Sensor Networks

In the following, we present a brief introduction to the RF energy harvesting issue to clarify the premises that were the basis of our research. The experiment that we propose tests the hypothesis that RF energy that accumulates in the car cabin during an outgoing voice call, video call or data transmission through 2G, 3G, 4G and 5G networks is sufficient to be captured and converted into usable electrical energy. The originality of the research related to our article consists of the method of measurement chosen, the specific setting (the interior of the car) and the proposed scenarios (underground parking, normal parking, 4G, 3G emission, etc.). The subsequent applicability to the design of a complete RF energy harvesting system that allows the effective use of the electromagnetic field that exists in the vehicle by capturing radio waves is quite a large issue. Being a common situation, often encountered in the context of the urban population (frequent trips by car throughout the day, considerable time spent in the car, intensive use of mobile phones in the car), we consider it a very plausible example of generating EMFs, which can be used to substantially reduce the consumption of conventional electricity involved even in daily activity during driving with vehicles (sensors, GPS devices, tablets, etc.).

Identifying the most efficient renewable energy sources is a constant concern for energy policymakers worldwide. Today, sources such as solar, wind, hydroelectric, thermal, chemical, kinetic and radio frequency energy offer opportunities to capture and convert ambient energy into usable electrical energy, enabling greater energy efficiency, sustainability and the development of autonomous and self-powered systems [25]. Moreover, a novel communication mechanism that enables devices to communicate by backscattering ambient RF signals was also introduced [26,27]. This innovative and appealing possibility can reduce costs in a very promising manner because backscattering TV signals and other sources of RF signals can have, at the same time, the role of a power source and a means of communication [27].

In completion, RF energy harvesting offers a renewable and environmentally friendly approach for powering low-power wireless devices and sensors, enabling wireless connectivity and reducing the reliance on traditional power sources.

There are several factors contributing to the growing interest in RF energy harvesting. The main factor among them is the proliferation of wireless devices that can be seen as EMF sources [10,15,28–31].

In order to understand the full potential of the RF energy harvesting process, in light of the latest developments, it can be useful to consider the evolution of the technology and applications that lies behind the concept. The two key elements in RF energy harvesting systems are the antenna and rectifying circuit, also known as the rectifying antenna. The performance efficiency of each RF energy harvesting system depends on the antenna efficiency and rectifying circuit efficiency. With advancements in technology, researchers and engineers have focused on improving the efficiency of RF energy harvesting systems, miniaturization and the integration of RF energy-harvesting components. This has led to the development of compact and lightweight RF harvesting modules that can be integrated into various devices and systems, including wearables, IoT devices and Wireless Sensor Networks [10]. In light of technology advancements, traditional RF energy harvesting has focused on specific frequency bands. However, recent advancements have enabled the harvesting of energy from multiple frequency bands or even wideband signals [32]. This allows for the better utilization of available RF sources and increases the potential for energy harvesting in various environments.

All of these chronological advancements have led to a diversity of applications of RF energy harvesting in various fields, such as Wireless Sensor Networks for environmental monitoring, industrial automation, smart cities, wearable devices, remote monitoring systems and low-power IoT devices, among others [33].

The development of battery-free or maintenance-free IoT devices will contribute to the faster development of the IoT, contributing to several aspects that drive economic growth and innovation [34]. For example, by enabling real-time monitoring, predictive maintenance, and automation, IoT devices will help businesses streamline their operations, reduce costs, enhance productivity [35], improve supply chain management, enhance customer experiences and identify new revenue opportunities [36,37]. Data-driven decision making facilitated by IoT devices enables businesses to stay competitive in today's fast-paced economy. These devices enable automation, optimization and intelligent decision making, leading to increased efficiency, reduced waste, improved safety and enhanced customer experiences. By optimizing resource utilization, reducing energy consumption and enabling the efficient monitoring and management of assets, IoT devices promote sustainable business practices. This not only reduces costs but also addresses environmental challenges, making businesses more resilient in the face of economic and environmental uncertainties [38–40].

Along with the development of IoT devices, RF energy harvesting has tremendous implications for WSNs.

The development of WSNs itself is closely related to one of the IoT devices presented above. Improved sensing capabilities have expanded the range of applications for WSNs across industries such as agriculture, healthcare, environmental monitoring and smart cities [41–43].

Most recently, WSNs have started to leverage artificial intelligence (AI) and machine learning (ML) techniques [44–47]. AI and ML algorithms can analyze sensor data, identify patterns and make intelligent decisions. This integration enables WSNs to adapt dynamically to changing environments, optimize resource allocation and improve system performance.

In conclusion, RF energy harvesting holds significant potential for the future development of the IoT and WSNs, providing a sustainable and reliable power source for these devices that can significantly extend their lifetime.

Moreover, RF energy harvesting allows for more flexible and scalable deployments, even in remote or hard-to-reach locations, facilitating the expansion of IoT devices and sensors. RF energy harvesting can be combined with other sources, such as solar or vibration, to create hybrid energy harvesting systems allowing IoT and WSN devices to leverage multiple energy sources, increasing the overall energy harvesting efficiency and ensuring continuous operation even in challenging environments.

Developing better methods to gain more efficient and reliable RF energy harvesting capabilities seems to be a path toward ensuring the future sustainable development of means designed to overcome future difficulties related to energy consumption.

Consequently, RF energy harvesting systems with high conversion efficiency need to be developed to power IoT devices. As mentioned earlier, the conversion efficiency depends on the incident RF energy of the antenna elements. We hypothesize that, in an enclosed space (such as the cabin of a car), where there are sources of EMFs (such as a mobile phone, infotainment, etc.), enough RF power is generated to be suitable for capture and conversion into usable electrical energy for powering IoT devices.

## 3. Materials and Methods

The measurements in this study were performed in Bucharest, Romania, between 1 February and 1 April 2023 using a compact-sized car.

### *3.1. Measurement Equipment*

The measurements of the E-field strength (magnitude and distribution) were carried out using the LSProbe 1.2 Field Probe System [48]. The Field Probe System consists of an isotropic E-field probe connected through a fiber optic cable to a Computer Interface (CI-250). CI-250 was used to connect the isotropic field probe to a laptop. During all measurements, a continuous record of x-, y- and *z*-axis E-field values directly on the computer hard disk was performed. The E-field strength range of LSProbe 1.2 is from 0.1 V/m to 1 kV/m, in the frequency range of 0.3 to 6 GHz, and from 1 V/m to 1 kV/m, in the frequency range of 6 to 8.2 GHz.

### *3.2. Measurement Locations*

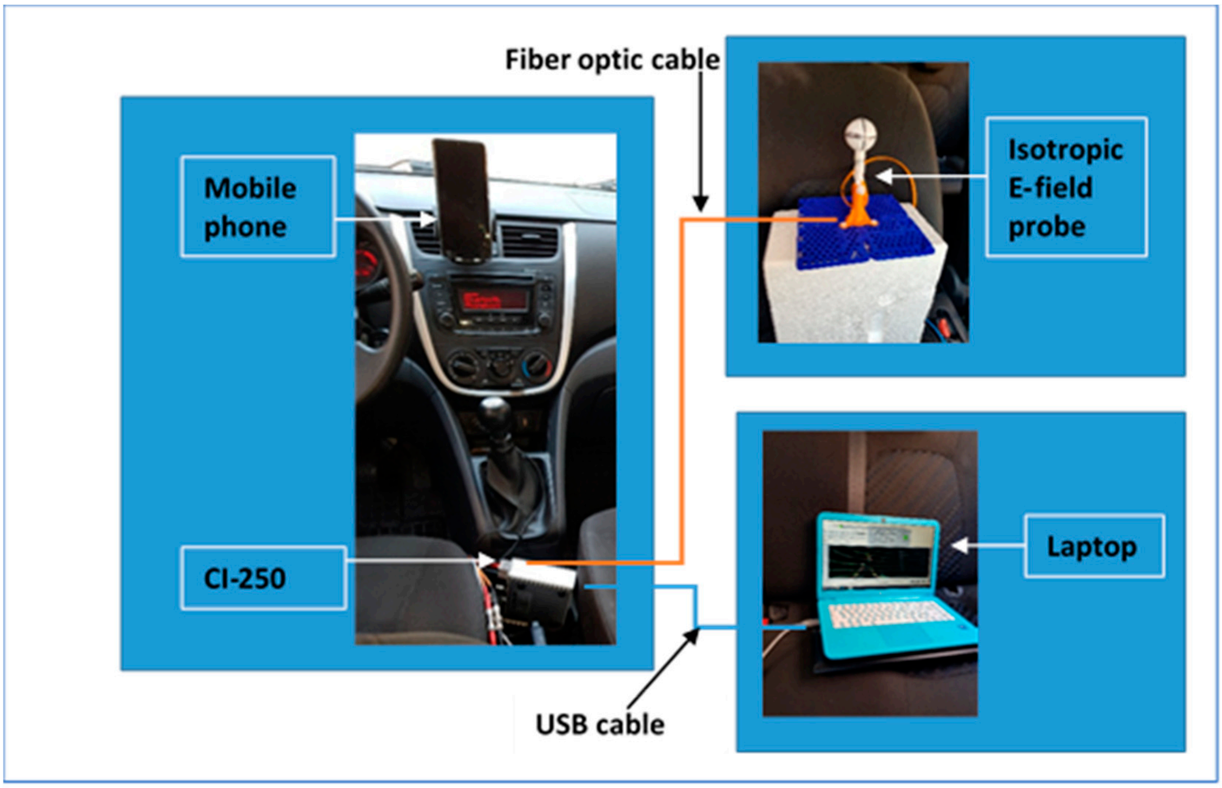
The measurements of the E-fields were carried out in two locations that represent the worst-case scenarios of using wireless communication in a vehicle.

Location 1 was an urban area with a Non-Line-of-Site (NLoS) to a base station antenna. All measurements were carried out in the location with an NLoS to the base station antenna because previous investigations have shown that the user terminal (UT) in GSM, UMTS, LTE and 5G use Adaptive Power Control (APC) [49–51]. This means that, when UT is in a location with an LoS to the base station antenna, the UT decreases the power level in correspondence with the APC algorithm to achieve the lowest possible transmit power [49,50]. Hence, in the NLoS location, the UT is transmitted with higher power compared to that of the LoS location.

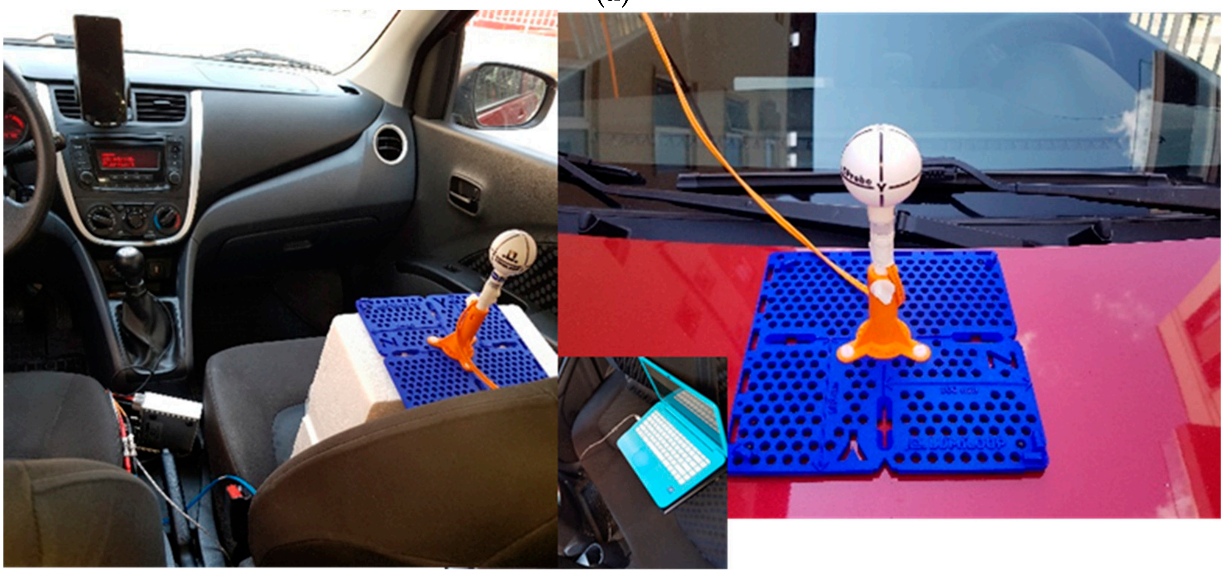
Location 2 was an underground car park in the Centre of Bucharest.

### 3.3. Measurement Procedure and Scenarios

The mobile phone was placed at one position on a car dashboard in a phone holder for testing each scenario. The LSProbe was also placed in one position (in the seat next to the car driver) on a styrofoam block (see Figure 1). This arrangement allowed us to keep the same distance between the mobile phone and the LSProbe for each scenario.




(**a**)



(**b**)

**Figure 1.** Overview of the experimental setup: (**a**) block diagram and (**b**) photos.

Because the availability of RF energy depends on both the surrounding environment (e.g., base station antenna distance, LoS or NLoS, etc.) and cellular network traffic, the measurements were divided into two groups: measurements of EMFs in different wireless communication scenarios and control measurements of EMFs.

Details of the wireless communication scenarios are summarized in Table 1. The conditions for the control measurements of the EMFs are summarized in Table 2.

**Table 1.** Wireless communication scenarios.

| Scenario | Sub-Scenario | Description | User Terminal Network Mode |
|---|---|---|---|
| Scenario 1: voice call | Sub-Scenario 1a | voice call set up via GSM network | 2G only |
| | Sub-Scenario 1b | voice call set up via UMTS network | 3G only |
| | Sub-Scenario 1c | voice call set up via LTE/5G network | 5G/LTE/3G/2G (auto connect) |
| Scenario 2: video call | Sub-Scenario 2a | video call set up via GSM network | 2G only |
| | Sub-Scenario 2b | video call set up via UMTS network | 3G only |
| | Sub-Scenario 2c | video call set up via LTE network | LTE/3G/2G (auto connect) |
| | Sub-Scenario 2d | video call set up via 5G network | 5G/LTE/3G/2G (auto connect) |
| Scenario 3: data usage (Mobile Hot Spot) * | Sub-Scenario 3a | data transmission via UMTS network | 3G only |
| | Sub-Scenario 3b | data transmission via LTE network | LTE/3G/2G (auto connect) |
| | Sub-Scenario 3c | data transmission via 5G network | 5G/LTE/3G/2G (auto connect) |

* UT is configured as a Mobile Hot Spot, and a laptop is connected to it.

**Table 2.** Conditions for control measurements of EMFs.

| Control Measurements | Conditions | Descriptions |
|---|---|---|
| Control 1 | outside the car | LSProbe is outside the car. UT is switched off. |
| Control 2 | inside the car | LSProbe is inside the car. UT is switched off. |

We measured the EMFs in each scenario at two locations: Location 1 and Location 2, described in Section 3.2.

The user terminal was configured to operate in different modes (2G only, 3G only, etc.) to perform the different sub-scenarios.

The duration of each voice call, video call and data transmission in each sub-scenario was 6 min. More than 1600 measurements of the E-fields for each sub-scenario were performed.

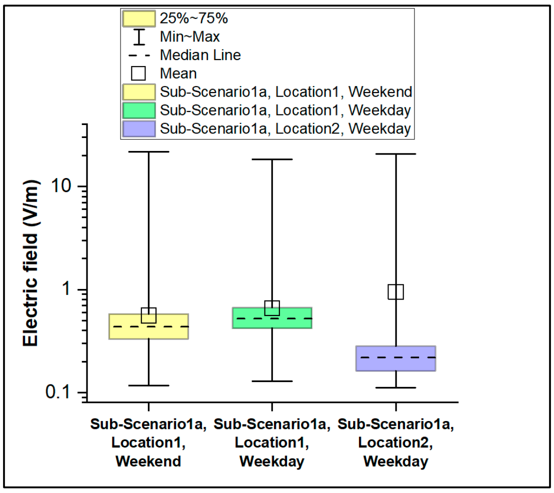
Measurements in each sub-scenario were performed on both weekdays and weekends.

To assess the background EMFs, we measured the EMFs at the beginning and the end of each measuring campaign. Control measurements were performed outside and inside the car. During these control measurements, the user terminal was switched off.

## 4. Results and Discussion

The results of the experiment are capable of sustaining our main hypothesis that an electromagnetic field is generated during mobile phone usage inside a vehicle, and the intensity of the field allows future experiments to be conducted to effectively harvest usable electrical energy from this field. In the following section, we explain the results that sustain this hypothesis of the research.

Figure 2 shows the measured electric field in the car during ongoing voice calls (Scenario 1 from Table 1) in each sub-scenario at two locations (Location 1 and Location 2) for weekdays and weekends. Comparing the results depicted in Figure 2, we can see that the highest measured value of the electric field appeared during the voice calls via the GSM network (Sub-Scenario 1a from Table 1). The results show that, regardless of the location and the day of the week (weekend or weekday) for Sub-Scenario 1a (see Figure 2a), the maximum measured value of the electric field remained almost unchanged, ranging from 18.39 V/m to 21.85 V/m. As seen in Figure 2b, 18.39 V/m (Location 1, Weekday) and 21.85 V/m (Location 1, Weekend) were measured for 2–5 s, after which the measured values decreased. These results were obtained because, in GSM mode during a voice call in the first 5 s, the output power level of the mobile phone was 33 dBm at GSM900 and 30 dBm at GSM1800, the maximum level. In the first several seconds, the user equipment occupied the control channel, called the random-access channel [49]. After that, the mobile phone decreased the power level in correspondence with the APC algorithm to achieve the lowest possible transmit power [49,50]. It can also be seen in Figure 2b that, at Location 2, the measured electric field throughout the 6-minute period remained high—about 15 V/m. The main reason for these results is that the phone was located in an underground car park, where the signal level from the base station was low. Therefore, the user equipment transmitted for all 6 min periods with a higher power compared to that of Location 1. Moreover, in Figure 2b, it can be seen that the mobile phone use in the circuit-switching mode in the GSM network [52] was transmitted in time slots. The maximum measured values of the electric field during a UMTS, LTE and 5G voice call are five to six times lower than those in the GSM network, between 3.46 V/m and 4.93 V/m. As seen in Figure 2d,f, lower values were obtained because, in the UMTS, LTE and 5G networks, the spread spectrum technic was used to establish a voice call with a lower spectral density. The mean values for Sub-Scenario 1a for different locations and days were 0.558 V/m, 0.653 V/m and 0.949 V/m, as shown in Table 3. From the results, we can conclude that RF energy accumulated in the car during ongoing voice calls in GSM, and the auto connect (5G/LTE/3G/2G) mode has the potential to be used as a source in energy-harvesting systems for low-power IoT devices.

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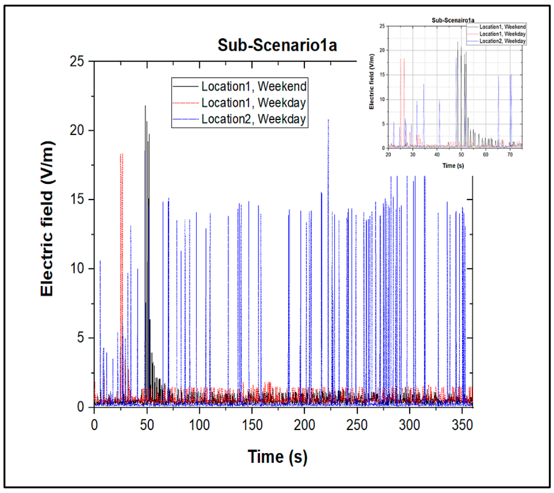


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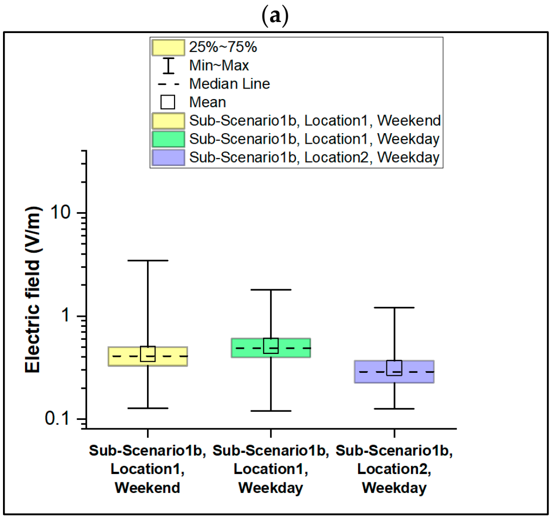


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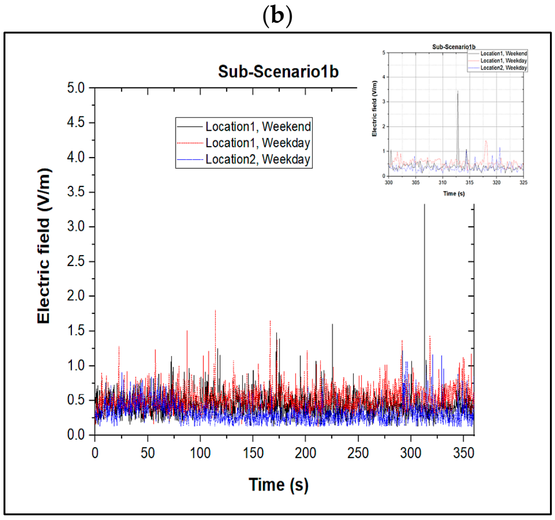
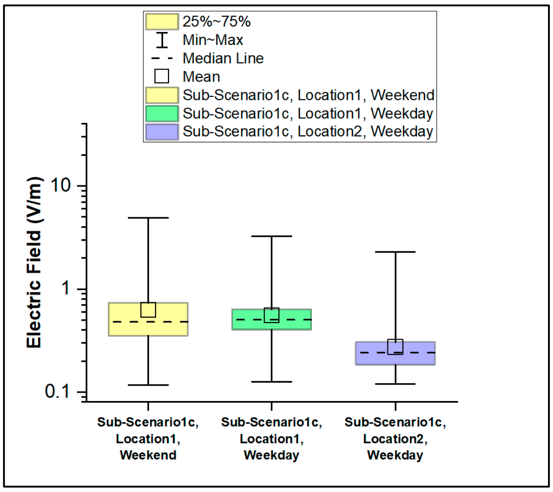
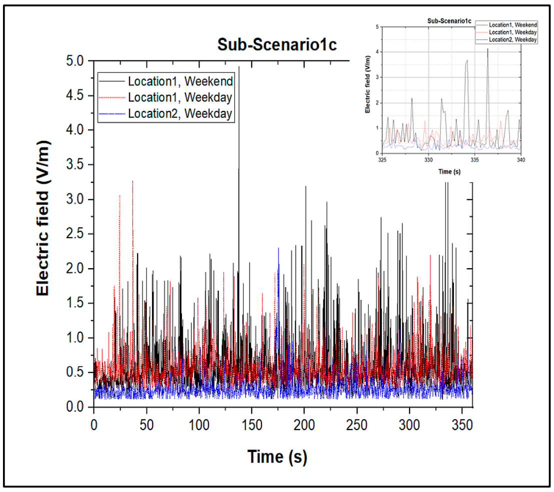



(d)

**Figure 2.** *Cont.*




(**e**)




(**f**)

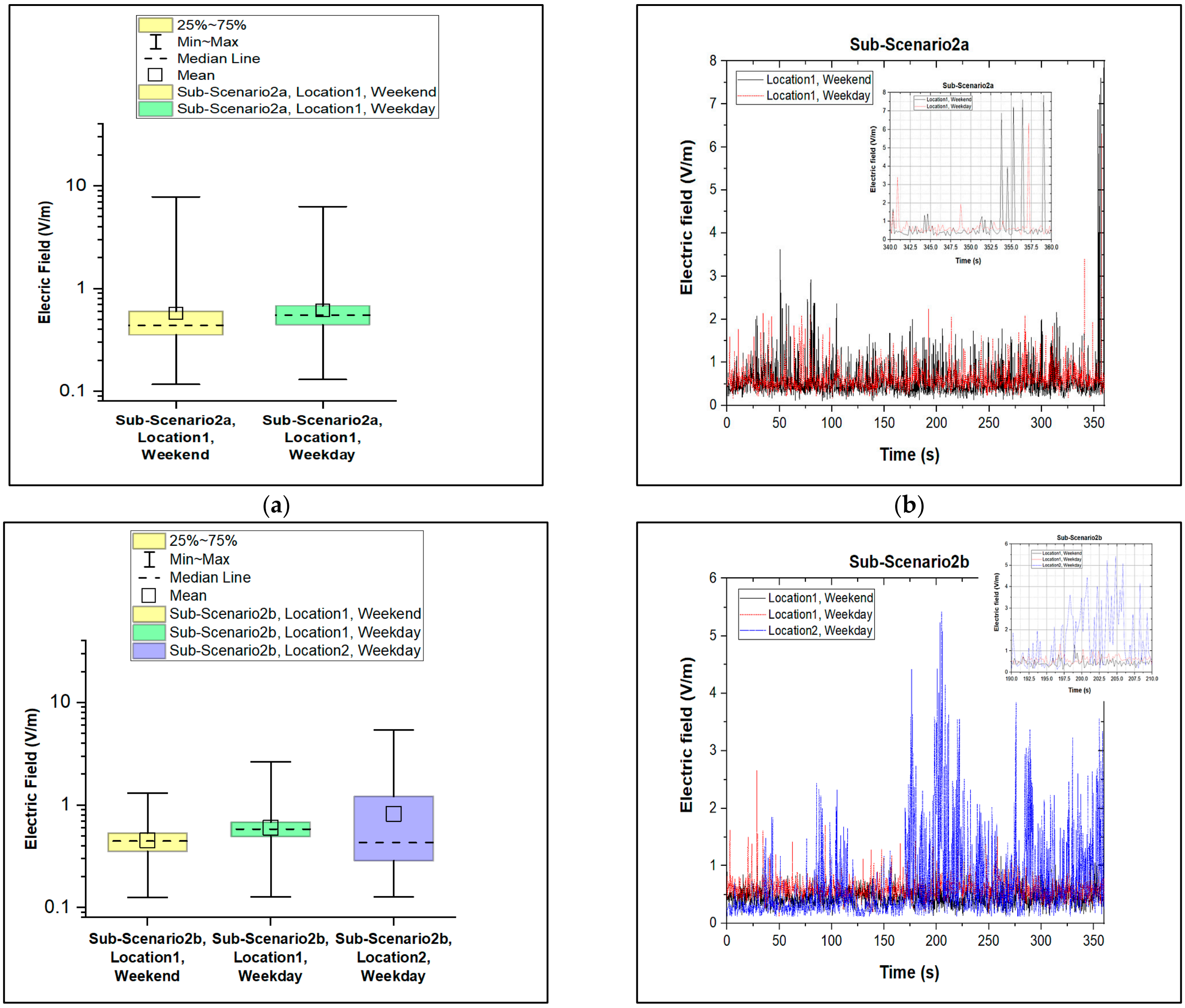
**Figure 2.** Boxplot charts and time variation of electric field for Scenario 1 (voice call) of the electric field measured in each sub-scenario at two locations (Location 1 and Location 2) for weekdays and weekends: (**a**,**b**) Sub-Scenario 1a: voice call set up via GSM network; (**c**,**d**) Sub-Scenario 1b: voice call set up via UMTS network; and (**e**,**f**) Sub-Scenario 1c: voice call set up via 5G/LTE/3G/2G (auto connect) network.

**Table 3.** Descriptive statistics.

| Scenario | Sub-Scenario | Mean | Minimum | Median | Maximum |
|---|---|---|---|---|---|
| Scenario 1: voice call | Sub-Scenario 1a, Location 1, Weekend | 0.559 | 0.116 | 0.436 | 21.846 |
| | Sub-Scenario 1a, Location 1, Weekday | 0.653 | 0.128 | 0.519 | 18.390 |
| | Sub-Scenario 1a Location 2, Weekday | 0.949 | 0.111 | 0.219 | 20.867 |
| | Sub-Scenario 1b, Location 1, Weekend | 0.428 | 0.127 | 0.407 | 3.461 |
| | Sub-Scenario 1b, Location 1, Weekday | 0.515 | 0.120 | 0.488 | 1.801 |
| | Sub-Scenario 1b Location 2, Weekday | 0.316 | 0.126 | 0.2886 | 1.217 |
| | Sub-Scenario 1c, Location 1, Weekend | 0.627 | 0.116 | 0.479 | 4.930 |
| | Sub-Scenario 1c, Location 1, Weekday | 0.559 | 0.126 | 0.504 | 3.279 |
| | Sub-Scenario 1c Location 2, Weekday | 0.275 | 0.120 | 0.242 | 2.307 |
| Scenario 2: video call | Sub-Scenario 2a, Location 1, Weekend | 0.573 | 0.116 | 0.439 | 7.846 |
| | Sub-Scenario 2a, Location 1, Weekday | 0.613 | 0.130 | 0.553 | 6.324 |
| | Sub-Scenario 2b, Location 1, Weekend | 0.452 | 0.125 | 0.443 | 1.306 |
| | Sub-Scenario 2b, Location 1, Weekday | 0.597 | 0.126 | 0.581 | 2.653 |
| | Sub-Scenario 2b Location 2, Weekday | 0.818 | 0.126 | 0.429 | 5.426 |
| | Sub-Scenario 2c, Location 1, Weekend | 1.196 | 0.111 | 0.635 | 11.061 |
| | Sub-Scenario 2c, Location 1, Weekday | 1.062 | 0.207 | 0.673 | 8.671 |
| | Sub-Scenario 2c Location 2, Weekday | 0.636 | 0.132 | 0.254 | 6.395 |
| | Sub-Scenario 2d Location 1, Weekend | 1.392 | 0.128 | 0.525 | 22.355 |
| | Sub-Scenario 2d Location 1, Weekday | 1.120 | 0.133 | 0.532 | 20.505 |
| Scenario 3: data usage (Mobile Hot Spot) * | Sub-Scenario 3a, Location 1, Weekend | 0.627 | 0.111 | 0.470 | 9.077 |
| | Sub-Scenario 3a, Location 1, Weekday | 0.709 | 0.126 | 0.489 | 7.585 |
| | Sub-Scenario 3a Location 2, Weekday | 0.727 | 0.133 | 0.403 | 5.751 |
| | Sub-Scenario 3b, Location 1, Weekend | 1.288 | 0.143 | 0.739 | 9.530 |
| | Sub-Scenario 3b, Location 1, Weekday | 0.924 | 0.131 | 0.607 | 7.552 |
| | Sub-Scenario 3c, Location 1, Weekend | 1.209 | 0.147 | 0.667 | 14.266 |
| | Sub-Scenario 3c, Location 1, Weekday | 1.058 | 0.145 | 0.673 | 19.225 |

* UT is configured as a Mobile Hot Spot, and a laptop is connected to it.

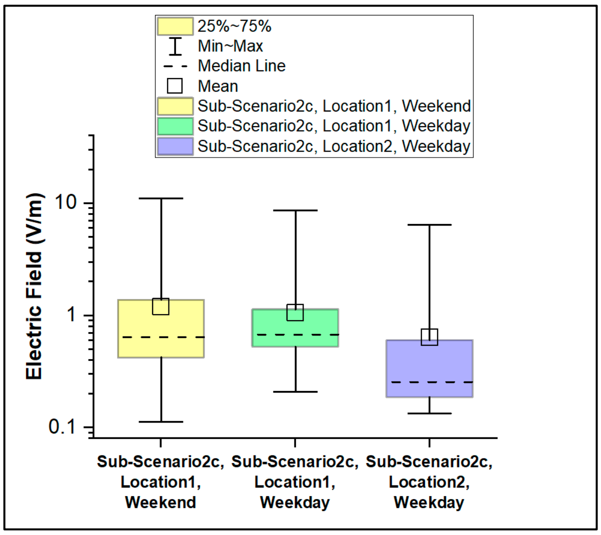
Figure 3 shows the measured electric field in the car during ongoing video calls (Scenario 2 from Table 1) in each sub-scenario at two locations (Location 1 and Location 2) for weekdays and weekends. As can be seen from the presented results in Figure 3, an ongoing video call was not able to be realized via the GSM and 5G network at Location 2 (underground parking). Comparing the results depicted in Figure 3a–h, we can see that the highest measured value of the electric field appeared during the video calls via the 5G network (Sub-Scenario 2d, see Table 3). These results were obtained because, in LTE and 5G, the uplink power control depended upon main factors such as several resource blocks, the modulation and coding scheme, path loss, UE maximum power, etc. Comparing the results depicted in Figure 3f,h with those in Figure 2d,f, it can be seen that, during ongoing video calls, the measured E-field increased due to the increased UE transmit power. We assume that the higher values of the electromagnetic fields were caused by the higher video image quality, which led to the transmission of a larger volume of data via the LTE and 5G networks and the allocation of more resource blocks. In LTE and 5G, the UE transmit power was increased in direct proportion to the number of allocated resource blocks. The mean values for Sub-Scenario 2d were 1.392 V/m and 1.120 V/m, as shown in Table 3. The generated electromagnetic fields during a video call in a car are suitable for the design of RF energy-harvesting systems for IoT devices and sensors.




(**a**) (**b**)

(**c**) (**d**)

**Figure 3.** *Cont.*

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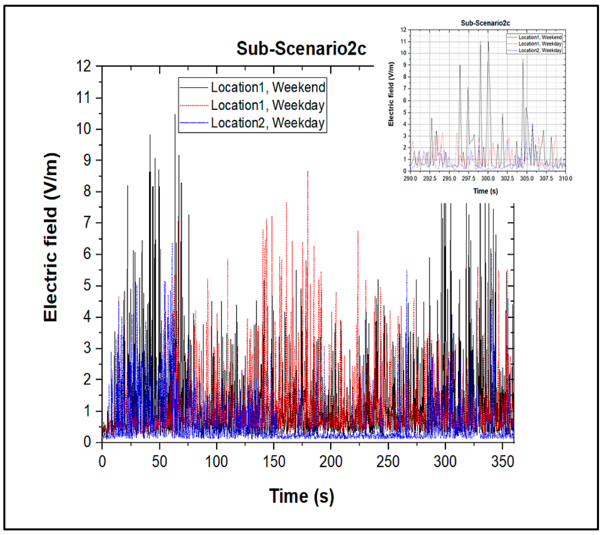


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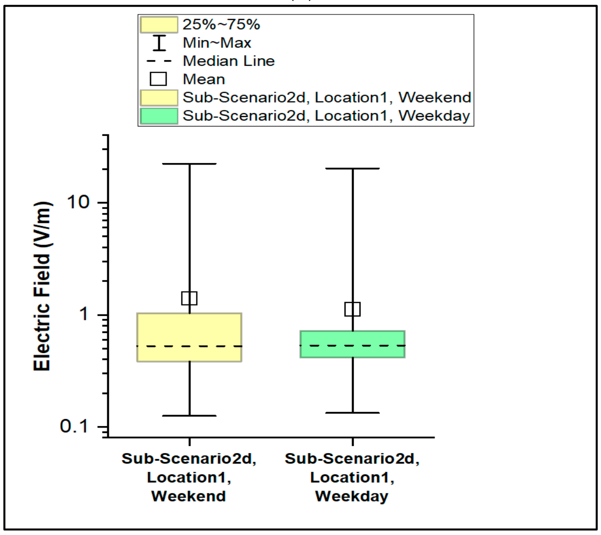


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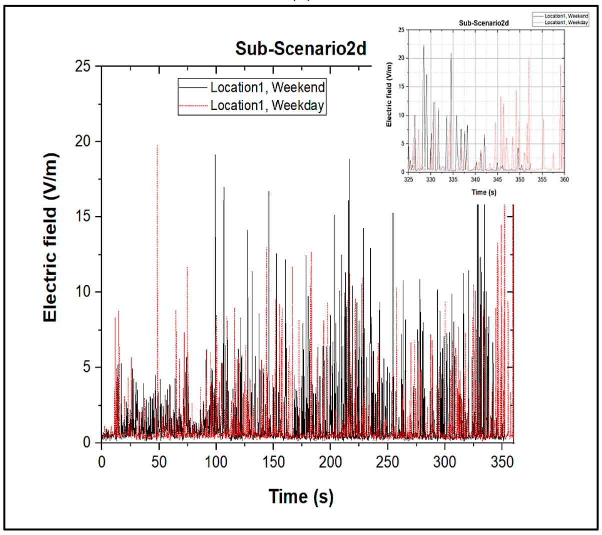



(**h**)

**Figure 3.** Boxplot charts and time variation of electric field for Scenario 2 (video call) of the electric field measured in each sub-scenario at two locations (Location 1 and Location 2) for weekdays and weekends: (**a**,**b**) Sub-Scenario 2a: video call set up via GSM network; (**c**,**d**) Sub-Scenario 2b: video call set up via UMTS network; (**e**,**f**) Sub-Scenario 2c: video call set up via LTE network; and (**g**,**h**) Sub-Scenario 2d: video call set up via 5G network.

Figure 4 shows the measured electric field in the car during data transmission (Scenario 3 from Table 1) in each sub-scenario at two locations (Location 1 and Location 2) for weekdays and weekends. In Scenario 3, we configured UT as a mobile hotspot. After that, we connected a laptop to the mobile hotspot. During the measurements in all sub-scenarios, we activated a video with 4k resolution on YouTube on the laptop.

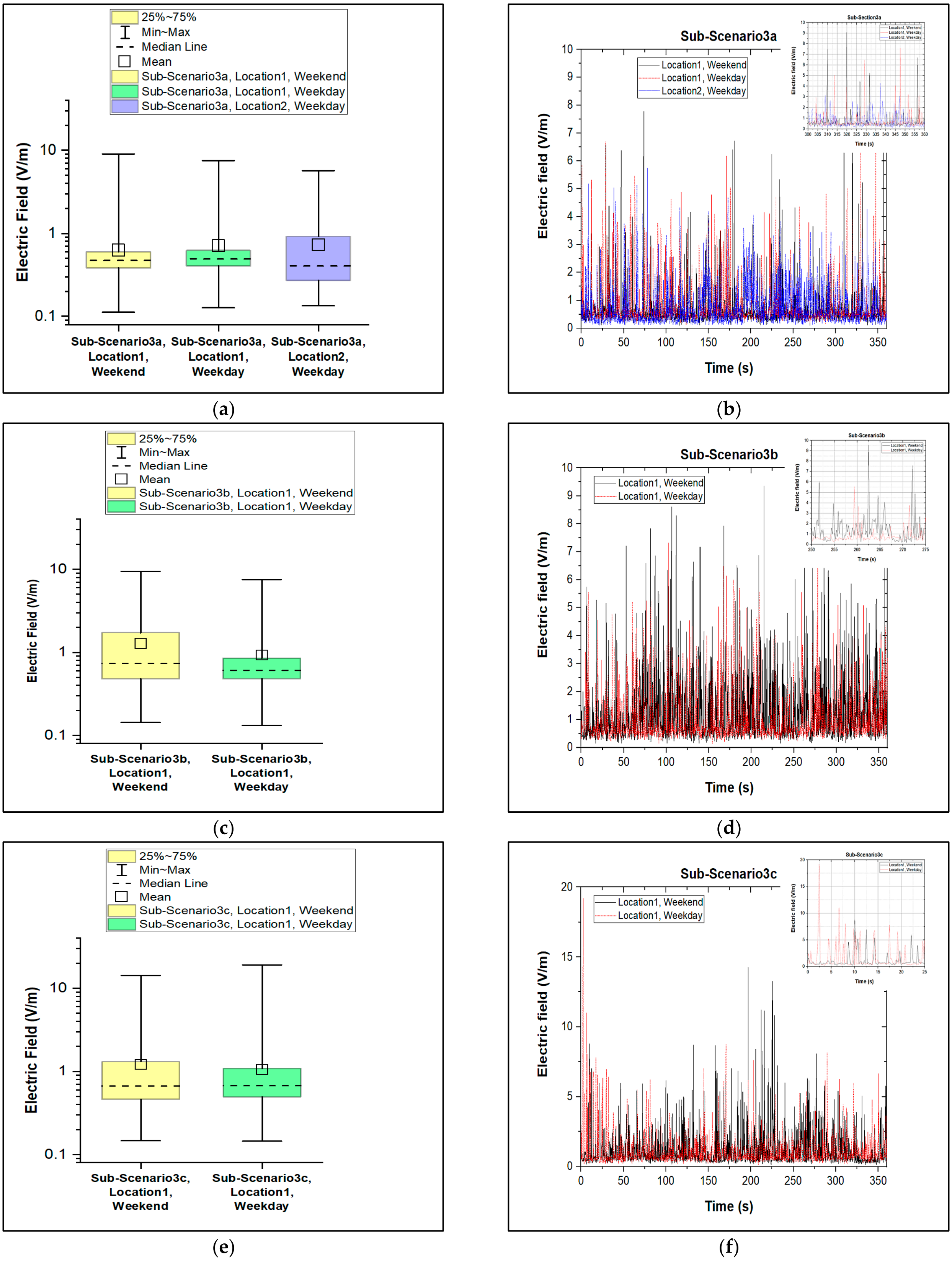



**Figure 4.** Boxplot charts and time variation of electric field for Scenario 3 (data transmission) of the electric field measured in each sub-scenario at two locations (Location 1 and Location 2) for weekdays and weekends: (**a**,**b**) Sub-Scenario 3a: data transmission via UMTS network; (**c**,**d**) Sub-Scenario 3b: data transmission via LTE network; and (**e**,**f**) Sub-Scenario 3c: data transmission via 5G network.

The results depicted in Figure 4 show that the electric field that accumulated in the car during data transmission exhibited slight variations depending on the day of the week in Location 1. The highest values of the electric field (14.266 V/m and 19.225 V/m, see Table 3) again were obtained during data transmission via the 5G network, i.e., for Sub-Scenario 3c. The obtained mean values in this sub-scenario were 1.209 V/m and 1.058 V/m. The mean values obtained were close to those of a video call (scenario 2) and were suitable for the design of RF energy-harvesting systems. In 5G, when a large data packet needs to be transmitted, UE can be indicated to activate a bandwidth part with a wide bandwidth comprising several continuous physical resource blocks. Comparing the results depicted in Figure 4a–f, we can see that the lower measured value of the electric field appeared during data transmission via the LTE network. As is known, in LTE, UE cannot transmit more than its maximum UE power, which is 23 dBm.

Control measurements of the electromagnetic field outside and inside the car were performed. The control measurements aimed to determine the RF energy in the vehicle when there was no source of an electromagnetic field in the cabin. In all control measurements, only the RF energy inside and outside the vehicle cabin, which was created by wireless cellular networks, wireless local area networks, etc., was evaluated. During the control measurements, the user terminal was switched off. Control measurements were carried out at the beginning and the end of each measuring campaign. Figures 5 and 6 show the measured electric field outside and inside the car at two locations (Location 1 and Location 2) for weekdays and weekends. The obtained mean values outside the car were 0.67 V/m and 0.83 V/m (at Location 1, weekend), 0.79 V/m and 0.83 V/m (at Location 1, weekday) and 0.21 V/m (at Location 2, weekday). These values were almost two times lower than the mean values for Scenarios 2 and 3. This comparison shows that the EMF generated by wireless cellular and local networks was attenuated by 25% in the vehicle due to the influence of the car cabin, interior, glass, etc. Comparing Figures 5 and 6, we can see that the mean values obtained during the control measurements in the car were about 25% lower than those outside the vehicle. It is also seen that the RF energy that accumulated in the car cabin during an outgoing voice call, video call or data transmission through 2G, 3G, 4G and 5G networks was sufficient to be captured and converted into usable electrical energy. Moreover, with the development of intelligent transport systems, connectivity between vehicles will increase. Hence, the number of wireless sources in the car will increase, and consequently, the application of RF energy-harvesting systems in cars will also increase.

Our hypothesis is also confirmed by the results of other authors. Sample and Smith [53] demonstrated the possibility of harvesting electrical energy directly from an RF source. They powered a commercially available thermometer/hygrometer with LCD using only RF power harvested from a TV transmission tower with the help of a WISP (Wireless Identification and Sensing Platform). The authors thus demonstrated on a small scale that the existence of EMF can be captured and used to give enough energy for small devices to be operational [53]. Moreover, in another experiment conducted in 2013, Piñuela et al. [20] demonstrated that ambient RF harvesting can be competitive with other technologies. The authors showed that the frequency of the RF sources is equivalent to DTV (digital television), GSM900, GSM1800 and 3G (mobile phones) bands that can be usual daily sources of energy, being operational in any urban or suburban area. Moreover, Celaya et al. 2020 [54] made measurements of RF–EMF exposure within urban public trams, showing a considerable amount of exposure in the case of 5G-type emitters, as the results in this study showed.

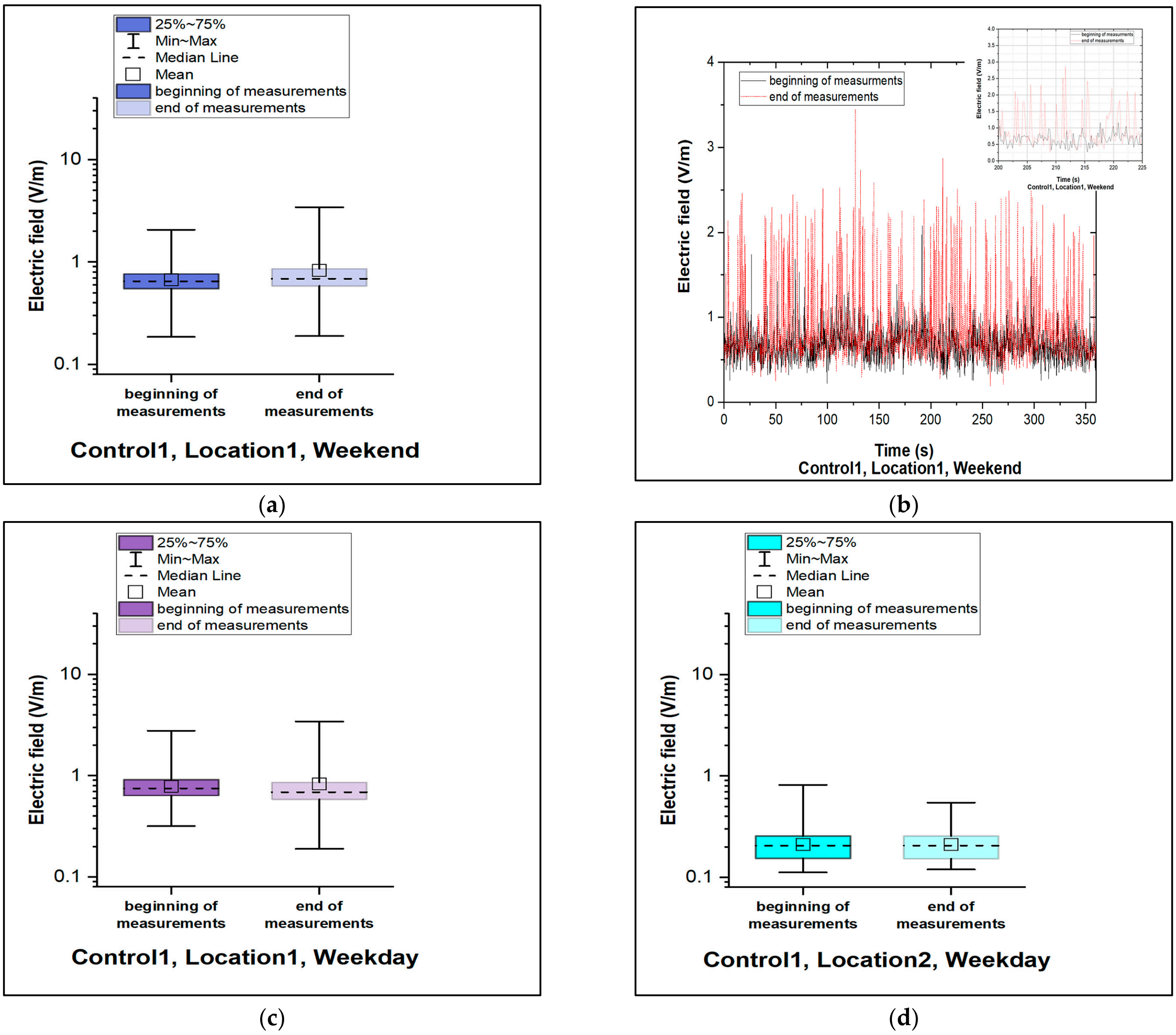
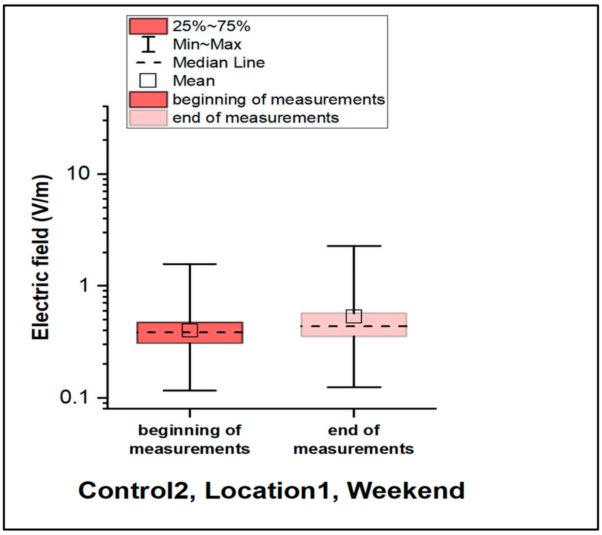
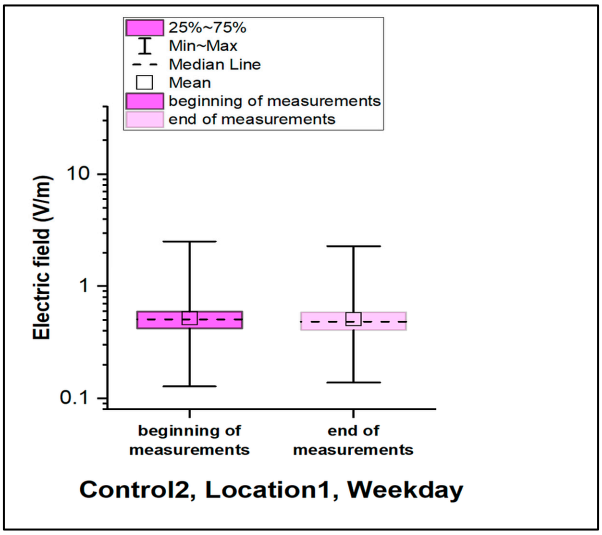



**Figure 5.** Control measurements. E-field measured outside the car at two locations: Location 1 and Location 2 for weekdays and weekends: (**a**,**b**) Control 1, Location 1, weekend; (**c**) Control 1, Location 1, weekday; and (**d**) Control 1, Location 2, weekday.

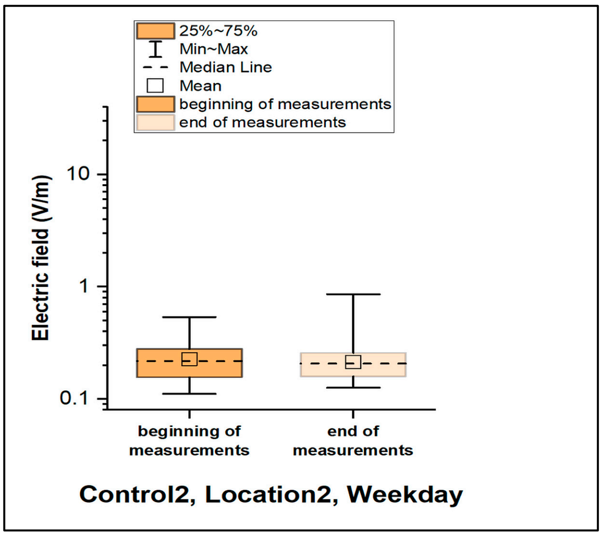
A comparison of the results obtained in this study with the results of another similar study [20] reported in the literature is given in Figure 7a,b to confirm our hypothesis. It can be seen that Piñuela et al. obtained average values of the electric field across London Underground stations (calculated from RF power density) varied between 0.02 V/m and 0.56 V/m. The obtained results in this work also show that the average mean value of the measured electric field outside the car (in free space) was 0.50 V/m, which was close to that measured by Piñuela et al. Furthermore, the mean values of the electric field in the car cabin during voice and video calls and data transmission via 2G, 3G, 4G and 5G cellular networks were comparable to or higher than those measured by Piñuela et al. Moreover, the data show that the highest maximal values (see Figure 7b) in the car cabin during voice and video calls and data transmission via 2G, 3G, 4G and 5G cellular networks were three to four times higher than those measured by Piñuela et al. [20] in the free space. Consequently, RF energy that accumulates in the car cabin during an outgoing voice call, video call or data transmission through 2G, 3G, 4G and 5G networks is sufficient to be captured and converted into usable electrical energy.




(**a**)




(**b**)

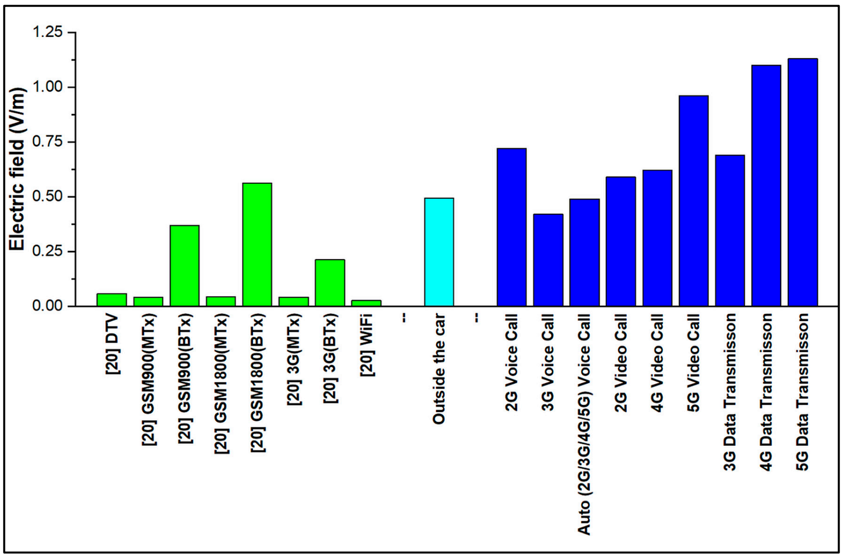



(**c**)

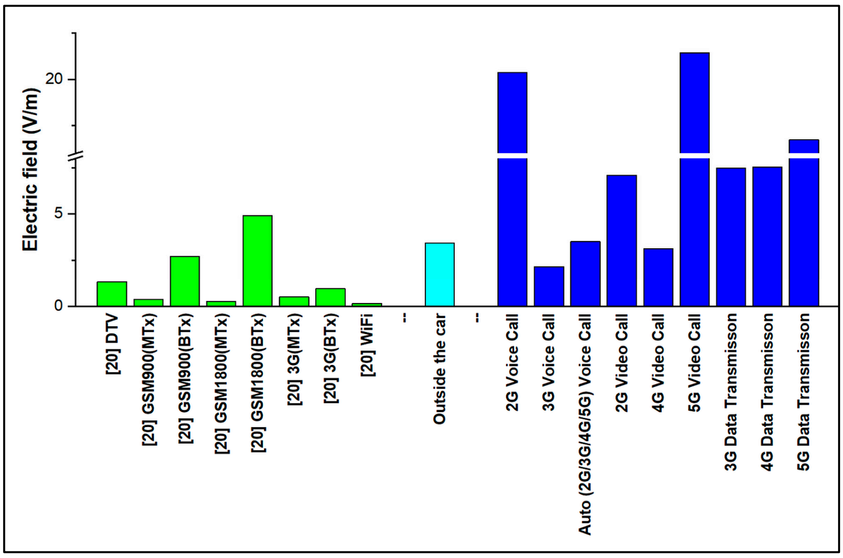
**Figure 6.** Control measurements. E-field measured inside the car at two locations: Location 1 and Location 2 for weekdays and weekends: (**a**) Control 2, Location 1, weekend; (**b**) Control 2, Location 1, weekday; and (**c**) Control 2, Location 2, weekday.

To show the applicability of our results, we carried out an additional experiment in a controlled environment (semi-anechoic chamber). In this experiment, the power received from three different antennas at a realistic electric field strength (obtained in this study) was measured in a semi-anechoic chamber (see Figure 8) to prove the hypothesis that EMFs emitted by wireless devices in a car can be used as a new energy source for ultra-low-power consumption devices.

The measurement setup contains a signal generator (SMB-100A, Rohde & Schwarz, Munich, Germany), a power amplifier (FLG-50F, Frankonia, Heideck, Germany), a Stacked Log Periodic Antenna (STLP 9128 C, Schwarzbeck, Schonau, Germany) as the transmitting antenna, a receiving antenna and a power meter. A horn antenna (BBHA9120D, Schwarzbeck, Schonau, Germany), a half wave dipole antenna and a flexible wearable patch antenna [55] were used as receiving antennas that received the electric field emitted from the STLP antenna at 2.4 GHz, 2.45 GHz and 2.5 GHz. The receiving antennas were located 3 m from the STLP antenna. The E-field probe (LSProbe 1.2 Field Probe System, LUMILOOP GmbH, Dresden, Germany) was placed in the location of the receiving antenna to determine the signal generator settings necessary to generate the appropriate electric field strength (for example, 1 V/m, 5 V/m, 10 V/m, and 20 V/m at 2.40 GHz, 2.45 GHz and 2.50 GHz). In this procedure, the relationship between field strength within the receiving antenna position (plane) and the forward power applied to the transmitting antenna was determined.




(**a**)




(**b**)

**Figure 7.** Comparison of results obtained in this study and a similar study [20]: (**a**) average values and (**b**) maximum values.

It can be seen in Figure 9 that, at 20 V/m, the power of the output of the horn antenna, dipole and flexible wearable antenna was 2613 µW, 338 µW and 197 µW at 2.4 GHz, respectively. At frequency 2.45 GHz, the power was 1634 µW (horn), 521 µW (dipole) and 205 µW (wearable antenna). At frequency 2.5 GHz, the power was 3650 µW (horn), 772 µW (dipole) and 240 µW (wearable antenna). This power was much higher than the power required in [20] of 3.2 µW (−25 dBm) to power small devices. As can be seen in Figure 9, the required power of 3.2 µW can be obtained at the output of the antennas at an electric field strength between 1 V/m and 3 V/m. These results prove the hypothesis that the

EMFs emitted by wireless devices in a car can be used as a new energy source to power battery-less wearable or IoT devices and can be used to design energy-harvesting systems with maximum conversion efficiency.

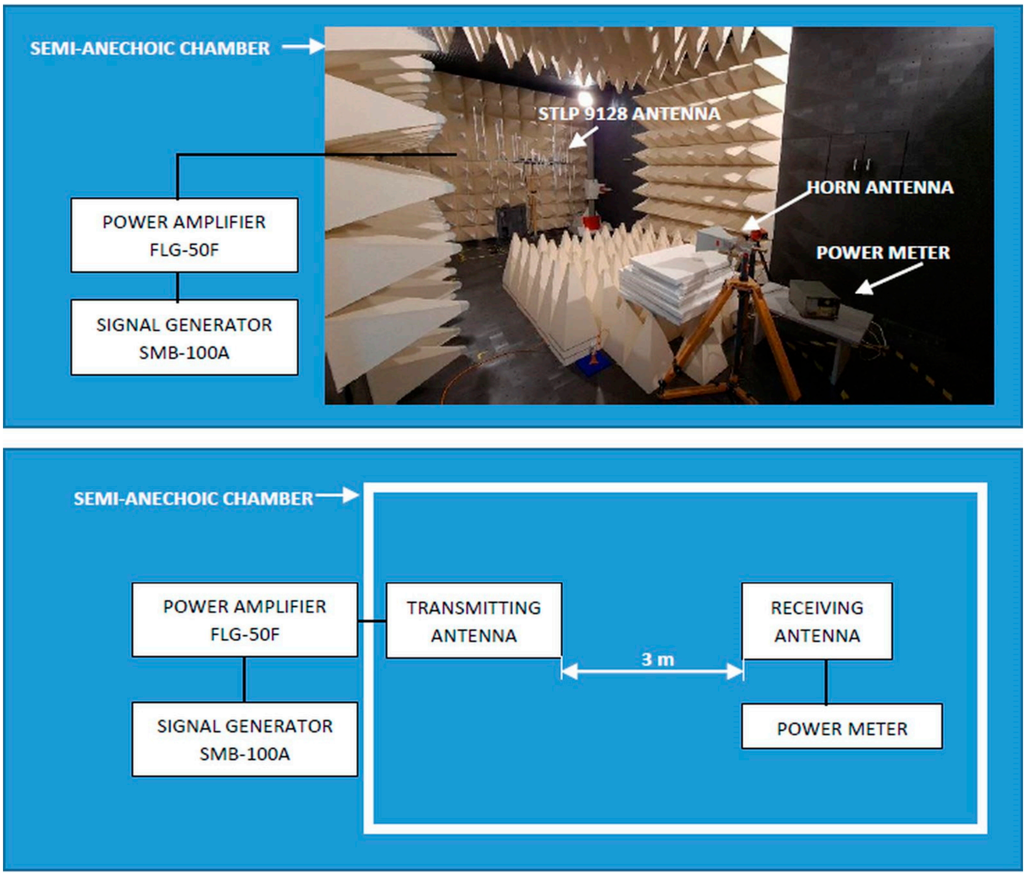
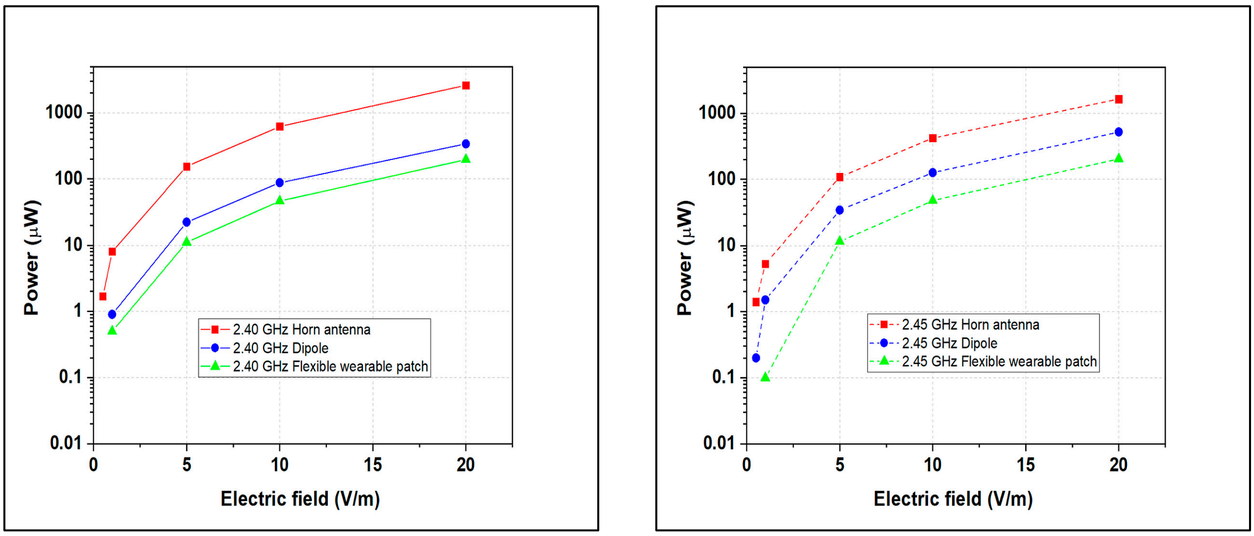
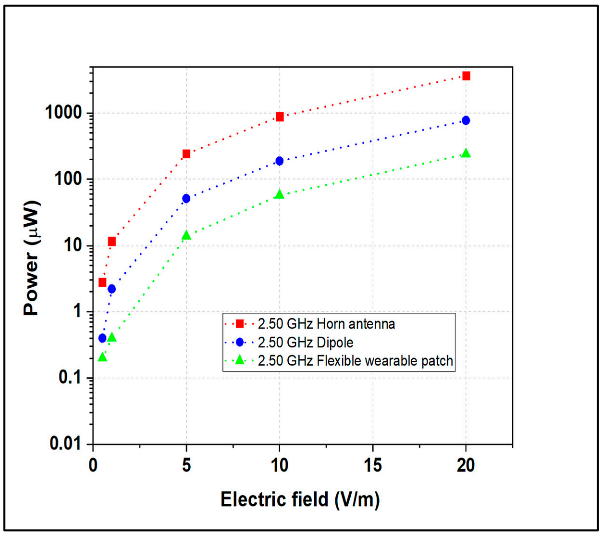



**Figure 8.** Measurement setup: photo and block diagram.




(**a**) (**b**)

**Figure 9.** *Cont.*




(**c**)

**Figure 9.** Power as a function of the electric field at: (**a**) 2.40 GHz, (**b**) 2.45 GHz, and (**c**) 2.50 GHz.

The EMFs emitted by wireless devices in a car also can be used for ambient backscatter. Ambient backscatter focuses on enabling communication among ultra-low-power devices using ambient RF as the only source of power, without requiring any additional power sources [26]. Recent work [27] on ambient RF power harvesting demonstrated prototype ambient backscatter devices requiring the power consumption of the analog portion of the transmitter (Tx)/receiver (Rx) of only 0.25 μW (Tx) and 0.54 μW (Rx), respectively. From the results presented in Figure 9, it can be seen that the power required for the transmitter or receiver of a backscatter device is achieved at an electric field intensity of 0.5 V/m to 1 V/m, regardless of the type of the receiving antenna (horn, dipole or flexible wearable antenna). From Figure 7a, it can be seen that, in the car cabin during voice and video calls and data transmission via 2G, 3G, 4G and 5G cellular networks, the mean values of the electric field strength vary between 0.5 V/m and 1.25 V/m; therefore, they are sufficient for use for ambient backscatter. Although our research has shown promising new results, we must be aware of potential research limitations, such as the following:

- Degree of Generalizability: The measurements were taken in a specific urban area, which may not reflect conditions in other urban areas or different geographical locations. Therefore, the generalizability of the findings to broader populations or regions may be limited.
- Controlled Environment: This experiment focused on two specific scenarios: when the car was in an open space without a direct line of sight to a base station antenna, and when the car was in an underground parking area. Although these scenarios provided valuable insight, they represent controlled environments with specific characteristics. The findings may not fully capture the variability and complexity of real-world conditions in which wireless devices are used.
- Interference and External Factors: The experiment did not explicitly address potential interference or the presence of external factors that could affect the E-field measurements. Various elements, such as nearby buildings, other wireless devices or environmental conditions, may introduce noise or distortions to the measurements, leading to potential inaccuracies or limitations in the conclusions drawn.
- Specific Application Scope: This experiment focused on the potential use of EMFs emitted by wireless devices in a car as an energy source for battery-less wearable or IoT devices. Although the findings support this hypothesis, the scope of the application may be limited to specific scenarios or devices. Further research is necessary to explore the applicability and feasibility of such energy-harvesting systems in diverse real-world environments and for different types of wearable or IoT devices.

- Long-Term Effects and Health Considerations: This experiment primarily focused on potential energy-harvesting applications and did not directly address the long-term effects or health considerations associated with exposure to EMFs emitted by wireless devices. To fully understand the implications of using these EMFs as an energy source, it is crucial to consider potential health risks and conduct thorough studies to ensure the safety and well-being of users.

The results of our experiment can be useful to the developers of future RF energy-harvesting systems. Even if we consider a small-scale experiment that involved a controlled location, and that the range of the direct application of the energy harvested inside a vehicle is limited to devices that can be useful for people taking a trip with the car, the results are promising and open a path to the future testing of the energy-harvesting process in different microenvironments.

In summary, the research results add value to the existing scientific literature by providing a comprehensive dataset specific to the car environment, offering a comparative analysis, exploring emerging technologies, analyzing variations and supporting the hypothesis of using EMFs for energy harvesting. These contributions expand the knowledge base, inform future research directions and enhance the understanding of the potential applications of EMFs in the context of energy harvesting and wearable/IoT device powering.

## 5. Conclusions

This paper experimentally evaluated electric fields inside a compact car for several realistic wireless communication scenarios and explored the possibility of using these EMFs in energy-harvesting applications. For each scenario, more than 1600 measurements of E-fields in an urban area in two cases (when the car was in an open space without a direct line of sight to a base station antenna, and when the car was in underground parking) were performed. The research results show that, inside the car, the maximum E-field emitted during GSM ongoing voice calls and 5G wireless data transmission was more than 20 V/m. During LTE data transmission, the maximum E-field was about 10 V/m. The obtained mean values in different sub-scenarios varied between 0.27 V/m and 1.39 V/m. Moreover, the electric field that propagated in the car during voice calls or data transmission exhibited slight variations depending on the day of the week. These results prove the hypothesis that the EMFs emitted by wireless devices in a car can be used as a new energy source to power battery-less wearable or IoT devices, and they can be used to design energy-harvesting systems with maximum conversion efficiency.

The results from this study provide the following:

- A comprehensive dataset of more than 1600 measurements of E-fields in different microenvironments and wireless communication scenarios;
- A comparative analysis of the E-field measurements in different wireless communication scenarios (during GSM voice calls, LTE and 5G data transmission, etc.), providing reliable knowledge on EMFs. The results will be used for future assessments of human exposure;
- Variations in E-fields over time and microenvironments for different communication scenarios, providing useful information for the design process of an RF energy system.

A possible future research direction that can properly complete these initial findings regarding the potential use of EMFs inside a vehicle can be a quantitative type of research in the form of a field survey based on a questionnaire designed to assess the perceptions and attitudes of people regarding the willingness to use such RF harvesting technology to power devices inside the vehicle.

RF energy harvesting holds immense potential for the future development of the IoT and WSNs. It addresses the power requirements and operational challenges of these devices, enabling sustainable, autonomous and scalable deployments. With RF energy harvesting, the IoT and WSNs can operate efficiently, reduce maintenance costs, and unlock new opportunities for applications in diverse sectors, contributing to the growth and advancement of the IoT ecosystem. Thus, the impact on a global scale can be a very important one, as we are all witnessing right now the proliferation of new models to integrate AI technology and other state-of-the-art machine learning aspects into the everyday use and consumption of products and services.

**Author Contributions:** Conceptualization, N.T.A., G.L.A., D.A.G. and I.P.G.; methodology, N.T.A., G.L.A., D.A.G. and I.P.G.; software, N.T.A. and G.L.A.; validation, N.T.A. and G.L.A.; formal analysis, N.T.A., G.L.A., D.A.G. and I.P.G.; investigation, N.T.A. and G.L.A.; resources, N.T.A. and G.L.A.; data curation, N.T.A., G.L.A., D.A.G. and I.P.G.; writing—original draft preparation, G.L.A.; writing—review and editing, N.T.A., D.A.G. and I.P.G.; visualization, N.T.A., G.L.A., D.A.G. and I.P.G.; supervision, N.T.A., G.L.A., D.A.G. and I.P.G.; project administration, G.L.A.; funding acquisition, G.L.A. and N.T.A. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The data presented in this study are available on request from the authors.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Abbreviations

| Acronym | Description |
|---|---|
| 2G | Second-generation cellular network |
| 3G | Third-generation cellular network |
| 4G | Fourth-generation cellular network |
| 5G | Fifth-generation cellular network |
| AI | Artificial Intelligence |
| APC | Adaptive Power Control |
| BLE | Bluetooth Low Energy |
| DC | Direct Current |
| DTV | Digital Television |
| E-field | Electric Field |
| EMFs | Electromagnetic Fields |
| GSM | Global System for Mobile Communications |
| IoT | Internet of Things |
| LCD | Liquid-Crystal Display |
| LoS | Line-of-Site |
| LTE | Long-Term Evolution |
| ML | Machine Learning |
| NLoS | Non-Line-of-Site |
| RF | Radiofrequency |
| UE | User Equipment |
| UMTS | Universal Mobile Telecommunications System |
| UT | User Terminal |
| Wi-Fi | Wireless Fidelity (a family of wireless network protocols based on the IEEE 802.11 family of standards) |
| WISP | Wireless Identification and Sensing Platform |
| WSNs | Wireless Sensor Networks |

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