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Ambient RF Energy Scavenging: GSM and WLAN Power Density Measurements

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***Abstract*—To assess the feasibility of ambient RF energy scavenging, a survey of expected power density levels distant from GSM-900 and GSM-1800 base stations has been conducted and power density measurements have been performed in a WLAN environment. It appears that for distances ranging from *25m* to *100m* from a GSM base station, power density levels ranging from $0.1mW/m^2$ to $3.0mW/m^2$ may be expected. First measurements in a WLAN environment indicate even lower power density values, making GSM and WLAN unlikely to produce enough ambient RF energy for wirelessly powering miniature sensors. A single GSM telephone however has proven to deliver enough energy for wirelessly powering small applications on moderate distances.**

I. Introduction

The continuous miniaturisation of electronics has led to an increasing interest in miniature, wireless autonomous sensor systems. This, in turn, has led to the need for low power electronics and alternatives for battery feeding. Of the different principles that exist for scavenging energy (e.g. vibration, heat), the scavenging of ambient RF energy is seen as an attractive possibility. With ambient RF energy we mean RF energy not specifically introduced for wirelessly powering an application, [1], [2], but RF energy available through pubic telecommunication services. Our main interest is in telecommunication services operating in the microwave region of the frequency spectrum, especially Global System for Mobile Communications (GSM) and Wireless Local Area Network (WLAN). For these services, printed antennas can be made with dimensions in the order of a few cm^2, satisfying our constraint for *miniature* sensors.

To assess the feasibility of employing the ambient RF energy supplied by the mentioned systems, we need to assess power density levels in different surroundings (e.g. inner city, outer city, industrial area, in house, outside, etc. for GSM) and settings (e.g. traffic: peak hours and off-peak hours for GSM and WLAN).

In Section II we will assess power density levels produced by GSM base stations. This assessment is based on measurement data gathered in different European countries over the last decade. Since data for WLAN is not as readily available as GSM exposure data, we have set up a WLAN power density measurement campaign. The measurement set up as well as the first exposure measurement results will be presented in Section III. In Section IV we will discuss the wirelessly powering of a miniature sensor by a GSM mobile phone, and in Section V we will state our conclusions with respect to the feasibility of ambient RF energy scavenging.

II. GSM Exposure Measurement Data

Due to a growing concern about a potential relation between GSM non-ionising radiation and health-risks, a number of European initiatives has been taken dealing with several aspects of RF exposure by the GSM system. The most important of these initiatives are COST-281: “Potential Health Implications from Mobile Communication Systems” [3] and the “European Information System on Electromagnetic Fields Exposure and Health Impacts” [4]. Within these initiatives, ample use has been made of the measurement data from several countries, gathered within COST Action 244bis: “Biomedical Effects of Electromagnetic Fields” [5].

This data has been used in this study to assess the power density levels supplied by GSM base stations. We have made a distinction between the GSM-900 (downlink: *935-960MHz*) and the GSM-1800 (downlink: *1805-1880MHz*) systems.

A. GSM-900

In Figure 1, the measured peak power densities as a function of the distance to the base station are shown. The data has been measured in Austria, Germany and Hungary [5]. Measured data from France and Sweden has not been used since the distance to the nearest base station was not known for this data.

All measurements used for this figure were single-frequency spot-measurements in the range *935-960MHz*. The measurements were taken in either two or three orthogonal directions, employing a bicone or log-periodic receive antenna. Traffic density as well as transmitting powers of the nearest base stations are unknown [5]. Since exposure limits differ for different countries, we do not expect the base station transmitting powers to be identical in all measurements.

Therefore, the power density levels should be regarded as indicative. The codes 'XY-a' connected to the different measurement sets indicate the area and the measurement characteristics as explained in the figure caption.

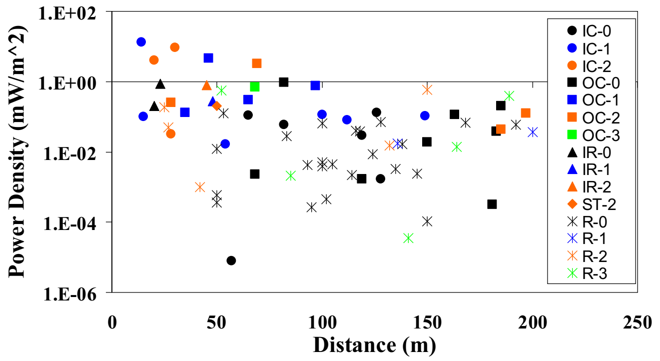

Fig. 1 Measured GSM-900 peak power density levels as a function of distance to the nearest base station. Data is taken from [5]. Code 'XY-a' indicates area and measurement site characteristics. XY: IC=Inner City, OC=Outer Country, IR=IndustRial area, ST=Small Town, R=Rural or country-side are. a: 0=outdoors on the ground, 1=outdoors on roof, terrace or balcony, 2=indoors, close to windows, 1.5m or less, 3=indoors, not close to windows.

At ground level we may expect the largest variation in power density, passing through the base station beam. In house and at an elevated level, these effects should be smaller. We observe indeed in Figure 1 a large variation in power density in the datasets IC-0, OC-0, IR-0 and R-0, all measured outdoors on ground level. If we remove these datasets from the figure, we get the results as shown in Figure 2.

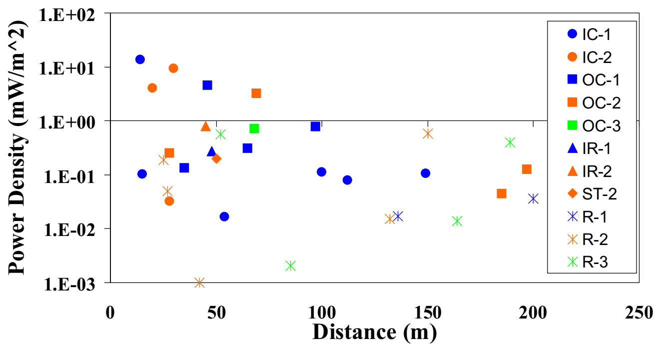

Fig. 2 Measured GSM-900 peak power density levels as a function of distance to the nearest base station. Data is taken from [5]. Same as Figure 1 but with data taken on ground level removed.

From this figure we may conclude that in between *25m* and *100m* from a GSM-900 base station, we may expect – indoors or outdoors on an elevated level – a power density between $0.1mW/m^2$ and $1.0mW/m^2$ (10^{-5}-$10^{-4}mW/cm^2$).

For measurements taken over the frequency band as a whole (*935-960MHz*), the summed power density as a function of distance to the nearest base station is shown in Figure 3. From this figure we may conclude that in between *25m* and *100m* from a base station, we may expect – indoors or outdoors on an elevated level – a summed power density between $0.3mW/m^2$ and $3.0mW/m^2$ ($3{\cdot}10^{-5}$-$3{\cdot}10^{-4}mW/cm^2$). Of course, the measurements over the whole frequency band depend strongly on the traffic density at the moment of measurement. A closer examination of the measurement data supplied by different countries [5] revealed that power density levels for measurements over the whole frequency band may differ by a factor one to ten from single frequency measurements. Details on GSM traffic at the moments of measurement are not available in [5].

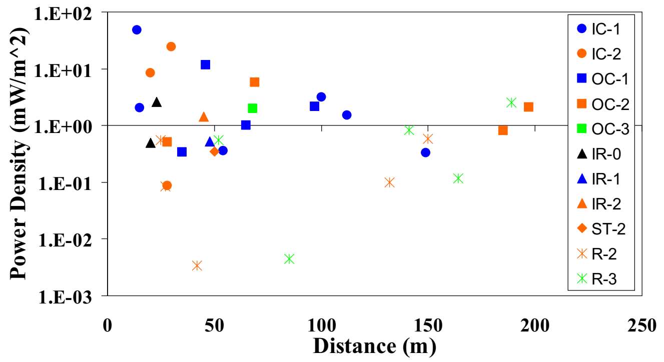

Fig. 3 Measured GSM-900 summed power density levels as a function of distance to the nearest base station, without data taken on ground level. Data is taken from [5].

B. *GSM-1800*

At the time the data as shown in Figures 1 to 3 was gathered (November 1996 to November 2000 [5]), GSM-900 was dominating GSM-1800. Therefore, more measurement data is available for GSM-900 exposure as for GSM-1800 exposure. Although the frequency of GSM-1800 has doubled with respect to GSM-900 and therefore the free space loss has been quadrupled, the ICNIRP exposure limit has only doubled [6]. Since for GSM-900, actual exposure levels are well beyond ICNIRP limits, we may expect for GSM-1800 similar power density levels as for GSM-900.

This assumption appears to be justified by measurements conducted in the UK at 118 locations at 17 sites for a mix of GSM-900 and GSM-1800 base stations [7] and by recent measurements in Australia for 60 base stations in five cities [8], see Figure 4. Exposure limits in Australia follow those of ICNIRP.

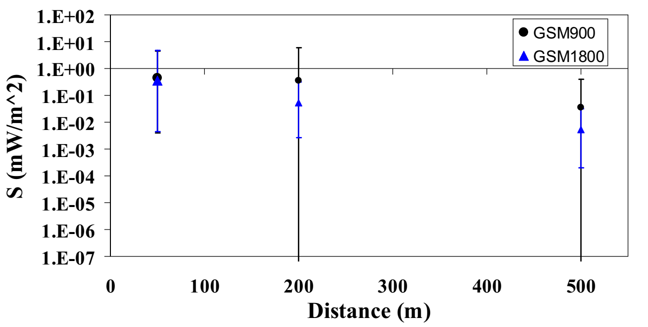

Fig. 4 Measured summed power density levels as a function of distance to the nearest GSM-900 and GSM-1800 base station. Data is taken from [8].

The measurements in [7] and [8] show that power density levels received from GSM-1800 base stations are – up to

100m - in the same order of magnitude as those received from GSM-900 base stations at a single frequency or summed for low traffic density situations.

From the assessment of the power density levels produced by GSM base stations, we may conclude that it will be very difficult at least to wirelessly power or charge a small sensor.

A WLAN router (base station) will transmit less power than a GSM base station. But since WLAN is more or less confined to indoor environments and the distance to a router is usually small, reflections and a low path loss could help in establishing higher power density levels.

III. WLAN Exposure Measurement

To examine these assumptions, we need to perform exposure measurements at different locations. We need to perform these measurements since published data on WLAN power density levels is not as readily available as for GSM. Measurements will be conducted following the recommendations of the European Conference on Postal and Telecommunications Administrations (CEPT) [9].

A. *Measurement Set Up*

A typical measurement set up is shown in Figure 5.

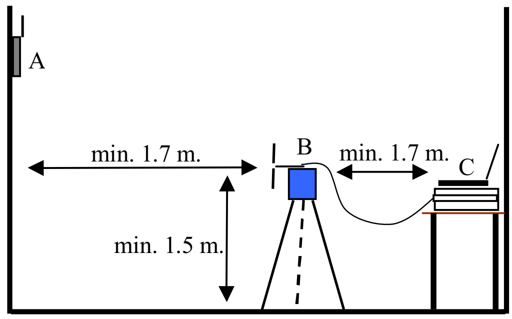

Fig. 5 Measured set up. A: WLAN router. B: Measurement antenna on tripod. C: Spectrum analyser and computer for data storage and processing.

The receive antenna is placed on a block of foam that is positioned on top of a wooden tripod and is kept at a distance of at least *1.5m* from the floor and at least *1.7m* from any wall. The receive antenna is a printed dipole antenna with integrated microstrip via-hole balun [10] that has been optimised for reduction of cable current distortion. The antenna will be rotated around its phase-centre to perform measurements in three orthogonal directions. Figure 6 shows the antenna with an indication of the phase centre.

Measurements (for three orthogonal directions) are taken at a specific position and four additional positions on a circle with a radius of *0.5m* around this position, see Figure 7.

A measurement consists of recording the maximum received power in a frequency sweep and the frequency for which this maximum occurs, using a spectrum analyser. This process is repeated continuously for half an hour. During a working day, several of these half-hour measurement sessions are performed. An average value is taken of the power received in the three orthogonal directions.

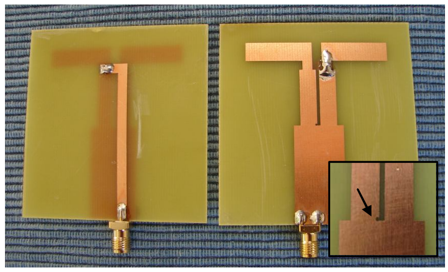

Fig. 6 Realisation on FR4 of a printed dipole antenna with integrated microstrip via-hole balun, back and front. Inset: indication of phase centre.

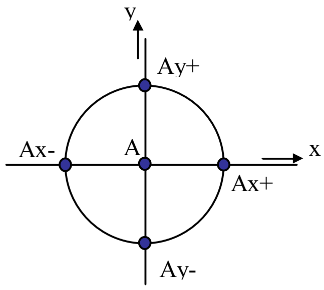

Fig. 7 Measurement positions at and around position A. The radius of the circle is *0.5m*.

B. *First Measurement Results*

Measurements have been performed at three positions on the 13th floor of the building of the Faculty of Electrical Engineering of Eindhoven University of Technology. The floor plan, with therein the positions of the WLAN routers and the measurement positions A, B and C is shown in Figure 8.

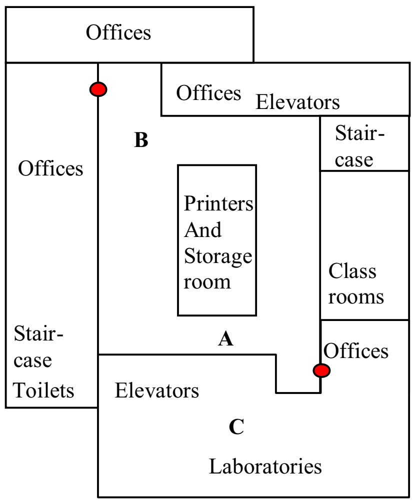

Fig. 8 Simplified floor plan of the 13th floor of the building housing the Faculty of Electrical Engineering of Eindhoven University of Technology. Red dots indicate the positions of the WLAN routers. Measurement positions are A (distance to router: *7.05m*), B (distance to router: *8.05m*) and C (distance to router: *12.30m*).

The measured power levels are divided by the effective area of the antenna - that is obtained through measurement of the gain - to get the received power densities. The first results are shown in Figure 9 as power density vs. distance to nearest WLAN router.

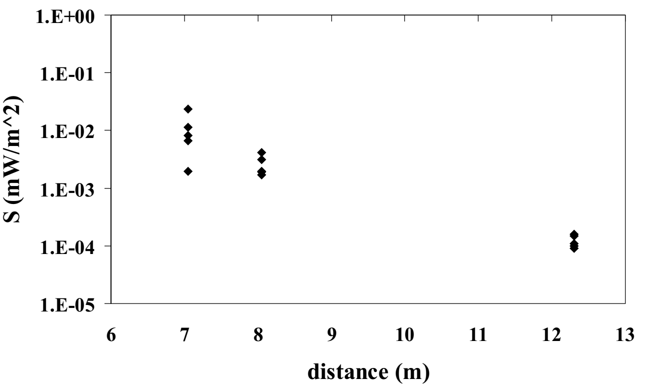

Fig. 9 Measured WLAN peak power density levels as a function of distance to the nearest WLAN router.

We see that the power density levels are at least one order of magnitude lower than those obtained close to a GSM base station. Therefore our assumptions regarding WLAN power densities prove to be wrong. It has to be noted though that during these first measurements the traffic density was extremely low (on average two connections at a time). However, it seems unlikely that in a WLAN environment small sensors can be powered for a reasonable long time. The idea of getting closer to an RF source as proposed in the concept of WLAN RF energy scavenging may be applied though to a GSM mobile phone.

IV. GSM Mobile Phone

In [11] the use of a GSM mobile phone is proposed as a source for RF energy scavenging. For a specific antenna, a scavenged power of *1.9mW* is predicted at a distance of *1m* from a GSM-900 mobile phone, transmitting at a power level of *2W*. This number however is rather optimistic and should be regarded as a theoretical maximum, assuming a *3dB* gain mobile phone antenna, polarisation and gain alignment of phone antenna and rectenna and a rectenna efficiency of *100%*.

Nevertheless, the concept seems to be feasible and therefore a microstrip patch rectenna for GSM-1800 has been designed following the procedure in [2]. The rectenna is realised on FR4 and connected to a LED for demonstration purposes. A GSM-1800 (*1W*) mobile phone is able to make the LED illuminate up to a distance of *20cm*, proving the concept. The system is shown in Figure 10.

Fig. 10 Rectenna feeding a LED. Wirelessly powered by a GSM-1800 mobile phone, transmitting at a peak-power level of *1W*.

V. Conclusions

It appears that for distances ranging from *25m* to *100m* from a GSM base station, power density levels ranging from $0.1 mW/m^2$ to $1.0 mW/m^2$ may be expected for single frequencies. For the total GSM downlink frequency bands these levels may be elevated by a factor between one and three, depending on the traffic density. First measurements in a WLAN environment indicate power density values that are at least one order of magnitude lower. Therefore, GSM nor WLAN is likely to produce enough ambient RF energy for wirelessly powering miniature sensors. By employing rectenna *arrays* [12] this ambient RF energy may be transformed to useable DC energy.

A single GSM telephone has proven to deliver enough energy for wirelessly powering small applications on moderate distances.

Acknowledgment

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