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Design of a low-cost triaxial 5G RF-EMF exposure sensor

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Abstract Subject Area(s)

["RF/Microwave","Risk assessment"]

Summary

A low-cost monitoring network, to measure the radio frequency electromagnetic field (RF-EMF) exposure induced by 5G, is required for risk communication and to support biological research into adverse health effects related to 5G technologies. Two different low-cost triaxial 5G RF-EMF exposure sensors were developed, calibrated, and tested. The sensors have a novel isotropic measurement design and are able to measure the exposure induced by 5G communication in the n77 (3300-4200 MHz) frequency band. The sensitivity of the Triple ADC and the Simultaneous ADC based triaxial sensor is 0.12 V/m and 0.04 V/m, respectively. The sensors were tested in an indoor (commercial 5G network) and an outdoor environment (private 5G network). The maximum measured electric-field level induced by 5G (n77 band) was 0.65 V/m (500 m from a commercial base station) and 2.69 V/m (50 m from a private base station), respectively. A temporal analysis of the measurement data was also performed.

Full abstract

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SUMMARY

A low-cost monitoring network, to measure the radio frequency electromagnetic field (RF-EMF) exposure induced by 5G, is required for risk communication and to support biological research into adverse health effects related to 5G technologies. Two different low-cost triaxial 5G RF-EMF exposure sensors were developed, calibrated, and tested. The sensors have a novel isotropic measurement design and are able to measure the exposure induced by 5G communication in the n77 (3300-4200 MHz) frequency band. The sensitivity of the Triple ADC and the Simultaneous ADC based triaxial sensor is 0.12 V/m and 0.04 V/m, respectively. The sensors were tested in an indoor (commercial 5G network) and an outdoor environment (private 5G network). The maximum measured electric-field level induced by 5G (n77 band) was 0.65 V/m (500 m from a commercial base station) and 2.69 V/m (50 m from a private base station), respectively. A temporal analysis of the measurement data was also performed.

INTRODUCTION

The fifth generation (5G) of telecommunications networks is currently the latest standard. 5G introduced the usage of new frequency bands such as n77 (3300-4200 MHz) with subbands n48 (3550-3700 MHz), and n78 (3300-3800 MHz). The carrier frequencies are higher compared to the carrier frequencies used in previous generations (2G-4G). There is public concern that the signals, more specifically the power of the electromagnetic fields (EMFs) induced by 5G communication, could cause health issues, and would affect the skin, eyes, and have adverse systematic effects [1] [2].

A low-cost monitoring network, to measure radio frequency (RF) electromagnetic field (EMF) exposure induced by 5G is required, is required for risk communication and to support biological research focusing on these topics [3]. Several universities already created low-cost designs to monitor exposure but these have some disadvantages. Deprez et al. [4] used a modular design to measure the RF-EMF exposure induced by different telecommunication wireless network technologies (GSM, UMTS, LTE, 5G). These sensors use a single dipole antenna to measure the RF-EMF exposure, which is insufficient to measure all three vector components of the EMF. Sârbu et al. [5] proposes techniques to perform real-time triaxial measurements but this requires expensive equipment, which is thus unsuitable for a monitoring network. As a result, a low-cost triaxial 5G RF-EMF exposure sensor needs to be designed and developed.

This paper discusses two novel 5G triaxial sensors designs, introducing several improvements compared to the state of the art. The new designs were developed, manufactured, calibrated and finally tested indoors (in an office) near a commercial 5G base station and outdoors near a private 5G base station.

METHODS

Design

Figure 1 shows the designs of the 5G RF-EMF exposure sensors, which are assembled in a weather proof enclosure made from polycarbonate (IP 66/67, manufactured by Fibox). The triaxial EMF exposure sensor uses three dipole antennas, which are positioned perpendicular to each other. The dipole antennas resonate at 3.86 GHz and have a -10 dB bandwidth of 800 MHz. The signal is first passed through an off-the-shelf multilayer bandpass filter (by TDK) before being measured by an HMC1120LP4E, a root mean square (RMS) detector by Hittite now Analog devices. The voltage at the output of the RMS detector is a linear-in-dB representation of the RF signal power. The RMS detector is capable to measure the power of RF signals within a frequency range of DC to 3.9 GHz while having a dynamic range of 70 dB. The lower detector limit is -65 dBm. The analog output of the RMS detector ranges from 0.32 to 2.7 V and is converted by an analog-to-digital converter (ADC). The measurements are processed by an ESP32 which is present on the Adafruit HUZZAH32 development board. The ESP32 is a 240 MHz dual core microcontroller (Tensilica Xtensa LX6) with 520 kB of SRAM. The ESP32 also supports Bluetooth v4.2 and WiFi 802.11 b/g/n. The latter is used to transmit processed measurement data, which ensures time synchronization. An expansion header was also present on the PCB of the sensors, to add other features such as local data storage (micro-SD card), a real time clock or as a debug port.

Two different designs, utilising different ADC setups have been developed, produced, and tested. The first design uses three separate ADCs (model: ADS1014), from now on denoted as Triple ADC based sensor. The second design uses a 4-channel simultaneous-sampling (SS) ADC (from Texas Instruments), from now on denoted as the simultaneous sampling ADC based sensor. The concept of the each sensor designs can be seen in Figure 1b and Figure 1c, respectively.

The ADCs use different communication protocols and thus different PCB designs. The Inter IC bus (I^2C) protocol is used to interface with the ADS1014. The ADS1014 has a resolution of 12 bits, programmable gain amplifier and a variable sample rate up to 3600 Sps (samples per second). A comparator is also included in the ADS1014.

The Serial peripheral interface (SPI) communication protocol is used to interface with the simultaneous-sampling ADC. The simultaneous ADC is a 4-channel simultaneous sampling ADC with a programmable resolution (16 to 32 bit), gain amplifier and sample rate up to 128 kSps.

The maximum achievable sample rate of the Triple ADC based sensor was 1600 Sps (for each channel) at a resolution of 12 bits. Thus, combined 4800 samples can be read each second. The simultaneous sampling ADC based sensor was able to achieve a sample rate of 32 kSps at a resolution of 16 bits.

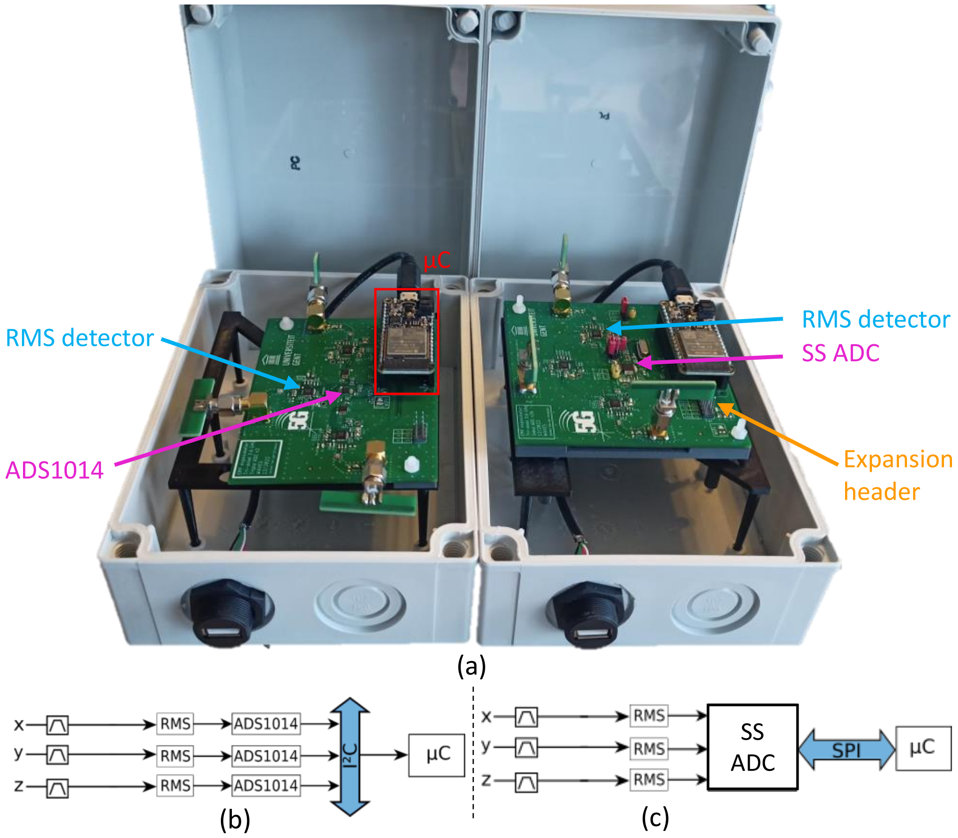


Figure 1: (a) Triple ADC and Simultaneous ADC based triaxial sensors. (b) Concept of the Triple ADC and (c) Simultaneous ADC based sensor. Both designs have the following items in common: three dipole antennas, multilayer band pass filters, RMS detectors and a microcontroller. The sensors are assembled in a weatherproof enclosure.

Calibration

The sensors are calibrated to ensure correct exposure measurements. The calibration procedure consists of two steps, an on-board and free-space calibration. The sensitivity and dynamic range of the sensors is determined during the on-board calibration. Subsequently during the free-space calibration, the relation between the measured power and RF-EMF exposure level is characterised.

On-board calibration

For the on-board calibration, the antennas are disconnected and replaced by 50 Ω terminations. Each channel, one at a time, of the triaxial exposure sensor is connected to a calibrated signal generator by Rohde & Schwarz (SMB100A) via an RF cable to determine the output voltage of the RF detector as a function of the incident power [6]. The output power of the signal generator is swept from -70 dBm to 8 dBm in steps of 1 dBm at a fixed frequency of 3.625 GHz (center frequency of the n48 frequency band). Next the output power of the signal generator is set to -20 dBm and the frequency is swept from 200 MHz to 4 GHz, in steps of 50 MHz, to verify the attenuation of the multilayer band pass filter.

Free-space calibration

The triaxial sensor (Figure 1a) is mounted on a tripod which is placed on a calibrated turn table by Maturo (model: TT 0.8 PF). Vertical and horizontal polarised antennas are used to transmit a 3.625 GHz signal (generated by SMB100A) towards the sensor sequentially. The sensor is placed at a height of 1.50 m and the distance from the transmit antenna to the sensor is 2.00 m. The setup is placed in a semi-anechoic chamber. The turn table is used to perform two full rotations at an angular velocity of 2°/s. Next, the triaxial sensor is replaced by an isotropic frequency selective field strength analyser manufactured by Narda (SRM-3006). The analyser is also used to measure the strength of the electromagnetic fields, which are generated by a signal generator, at 3.625 GHz (with an uncertainty of ± 4 dB). The results are then used to calculate the antenna aperture (AA) of the antennas used to measure the different components, which is based on the methods proposed by Aerts et al [7].

Energy consumption

Energy consumption is an important economic and ecological aspect when developing an appliance or sensor. The energy consumption is measured using an Energy meter manufactured by Perel. The Energy meter has a sensitivity of 0.1 kWh and 0.1 W. The energy consumption is monitored for 6 days.

In situ measurements

Measurements of 5G signals were performed indoors and outdoors with the triaxial sensors The indoor tests were conducted in an office building in Ghent, Belgium (commercial 5G network). The sensor was installed next to a window in a room located on the north side of the building, 500 m to the nearest base station. Outdoor tests were conducted in the Green Village in Delft, The Netherlands. This location was chosen due to the presence of a private 5G base station, which could be used to generate artificial traffic at a center frequency of 3.85 GHz and bandwidth of 100 MHz. The distance between the sensor and the base station is 50 m. The data obtained during the indoor and outdoor tests was stored on a micro-SD card, which was connected to the expansion header of the sensor.

RESULTS

Calibration

The results of the onboard calibration of the Simultaneous ADC based sensor can be seen in Figure 2a. All three orthogonal components (x,y,z) have a similar behaviour, $\Delta V(P_{in}) = \pm 0.05\,V$. The Z component of the Simultaneous ADC based sensor has a noise floor (NF) of -60.73 dBm which is the lowest of all axes ($P_{x,NF,SS}$ = -55.73 dBm and $P_{y,NF,SS}$= -57.73). The NF of the components (x,y,z) of the Triple ADC based sensor are -45.73 dBm,-60.73 dBm, and -58.73 dBm for $P_{x,NF,Triple}$, $P_{y,NF,Triple}$, and $P_{z,NF,Triple}$ respectively.

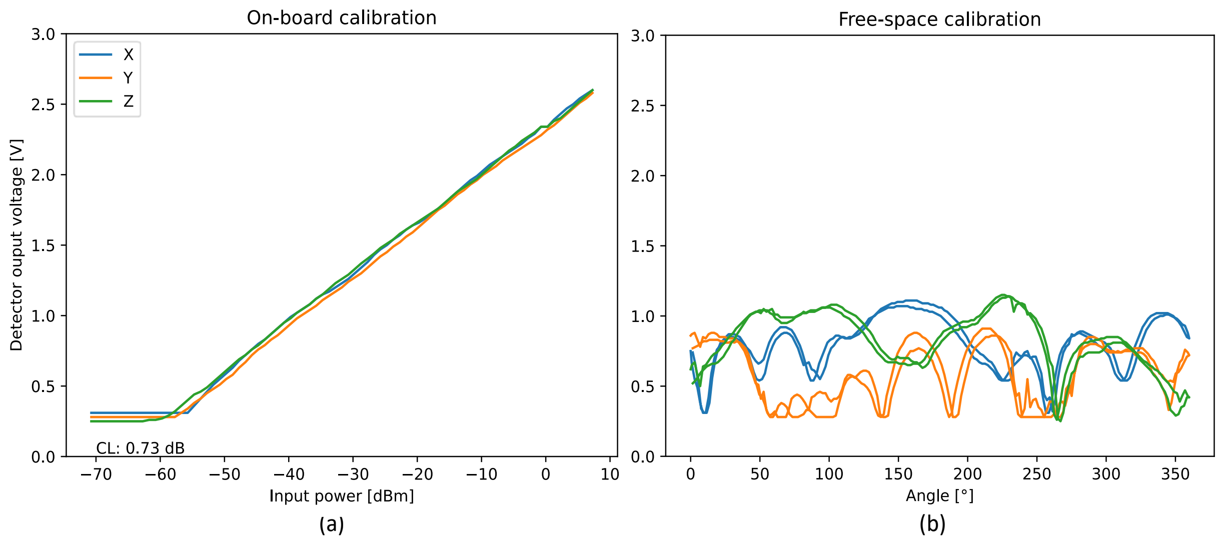


Figure 2: Results obtained during the (a) onboard and (b) free-space calibration of the Simultaneous ADC based sensor. A horizontally polarised antenna was used to transmit a signal to the sensor and measured voltage versus input power and angle is shown. The angle corresponds with the current rotation of the sensor (USB port) compared to the transmit antenna.

Figure 2b shows the results obtained during the free-space calibration. A horizontally polarised antenna was used to transmit a signal towards the sensor. The channel used to measure the y component has a vertical polarised antenna and is in this instance registering lower (median) powers compared to the other channels ($P_{x,SS,h\text{-}pol}$ = -43.8 dBm, $P_{y,SS,h\text{-}pol}$ = -48.3 dBm, and $P_{z,SS,h\text{-}pol}$ = -43.5 dBm). The opposite result can be spotted when a vertical polarised antenna is used to transmit the signal towards the sensor. This confirms the triaxial behaviour of the sensor. The sensitivity of the Triple ADC and the Simultaneous ADC based triaxial sensor is 0.12 V/m and 0.04 V/m, respectively. *Note: The RF front end (RFFE) of both sensors is identical, as a result the same sensitivity is expected. The difference is caused by a hardware issue in the channel used to measure the x component of the Triple ADC based sensor. The issue was not further investigated because it was a first prototype.*

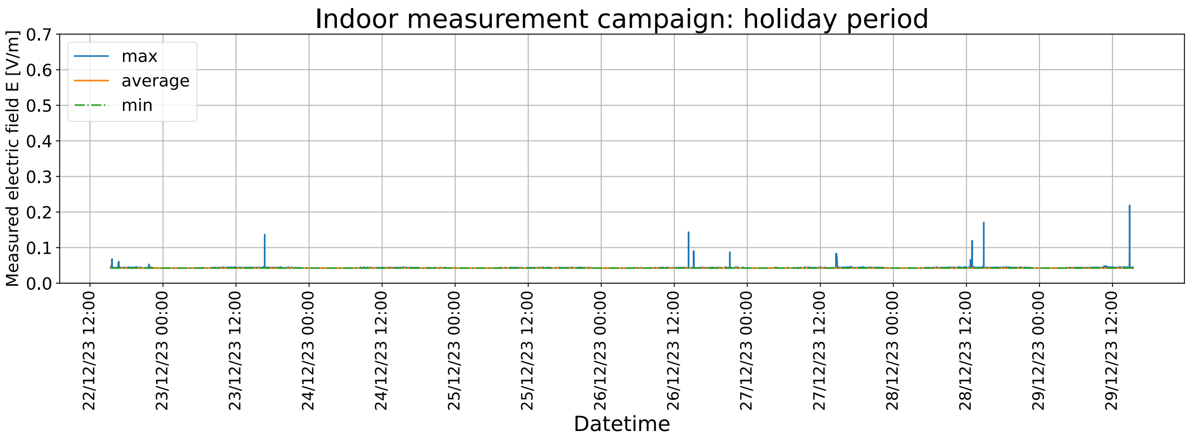
Energy consumption

The sensors consumed 0.2 to 0.3 kWh during a period (T) of 6 days (measured using an Energy meter). The Triple ADC based sensor consumed less energy than the Simultaneous ADC based sensor. The power draw of the sensors was also measured by the Energy meter. The Triple ADC and Simultaneous ADC based sensor draw 2.0 W and 2.1 W of power (P), respectively. The energy consumption EC_{calc} is also calculated based on the power drawn by the sensors (2). As a result, the sensors consumed 0.29 kWh and 0.30 kWh for the Triple and Simultaneous ADC based sensor, respectively.

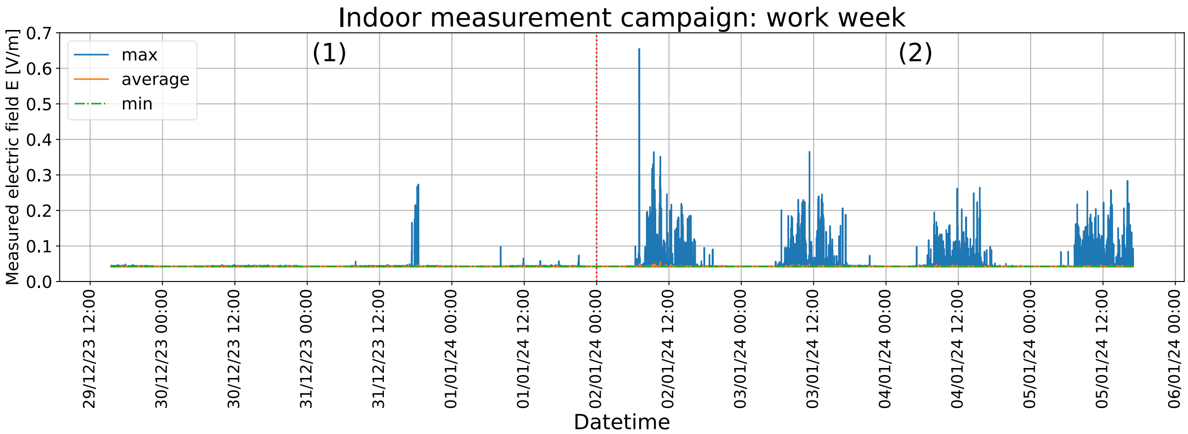
$$EC_{calc}[kWh] = \frac{P \cdot T[hours]}{1000} \qquad (2)$$

In situ measurements

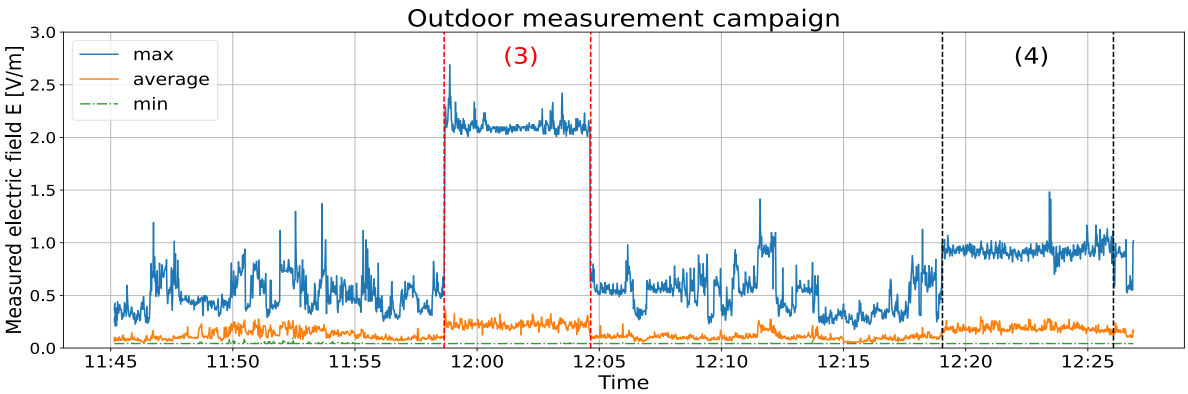
Figure 3 shows the results of the in situ measurements. The simultaneous ADC based triaxial sensor was tested indoors (Figure 3a and 3b) and outdoors (Figure 3c) to measure the total electric field induced by 5G communication (at 3.6 GHz). The sensor, which was placed indoor, measured for 14 days (starting on Friday the 22th of December). Figure 3a shows the results of the measurements that were recorded The office was closed from the 23th of December, 2023 until the 1st of January, 2024, hence the low recorded strengths of the electric field E. Only in a few instances electric field strengths above the noise floor (0.04 V/m) were recorded. Figure 3b shows the recorded electric field strengths during a work week. Every day there seems to be significant exposure between 8 AM and 6 PM. A day-night pattern can be observed. The maximum recorded exposure is 0.65 V/m, which satisfies ICNIRP guidelines [8]. Figure 3c shows the results of the outdoor tests. Only one user (UE) was connected to the 5G base station. Artificial traffic, such as a file download, was generated and started at 11:58 AM on the 24th of January, 2024 and lasted for 6 minutes (see Region (3) in Figure 3c). The maximum recorded exposure, when UE, sensor, and base station are collinear is 2.69 V/m, which satisfies ICNIRP guidelines. This configuration was chosen such that the sensor and UE are in the same beam. The median of the maximum exposure during the first file download test (Region (3)) was 2.10 V/m. The UE was also moved to a different location to measure when the UE, sensor, and base station are not collinear or not in the same beam, which can be seen in Region (4) in Figure 3c. The median of the maximum exposure during the second download test (Region (4)) is 0.92 V/m. Outside of Regions (3) and (4), the exposure caused by pilot signals and synchronisation signals is measured.



(a)



(b)



(c)

Figure 3: Measurement results obtained during (a) indoor measurements during holiday period, (b) indoor measurements during a work week, and (c) outdoor measurements. A day-night pattern can be observed in subfigure (b). Region (1) shows the exposure during the weekend. Region (2) shows the exposure during a work week. Region (3) shows the exposure when the UE, sensor, and base station are in the same beam. Region (4) shows the measured exposure when the sensor and UE were not in the same beam. The maximum recorded exposures indoor and outdoor are 0.65 V/m and 2.69 V/m, respectively.

CONCLUSIONS

Two different low-cost triaxial 5G RF-EMF exposure sensors were developed – one with three ADCs, one with one simultaneous ADC –, calibrated and tested in the field. The sensitivity of the Triple ADC and the Simultaneous ADC based triaxial sensor is 0.12 V/m and 0.04 V/m, respectively. The sensors were tested in situ indoor (commercial 5G network) and outdoor (private 5G network) and the maximum measured strength of the electric field induced by 5G was 0.65 V/m and 2.69 V/m, respectively. In the future, more triaxial nodes will be produced to create a 5G monitoring network in a Belgian city. Extra capabilities of the simultaneous ADC based sensor will also be investigated. The simultaneous ADC would in theory be able to sample all different symbols used to ensure 5G communication, when the subcarrier spacing is 15 kHz, because of its sample rate.

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