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Electromagnetic Biology and Medicine

ISSN: 1536-8378 (Print) 1536-8386 (Online) Journal homepage: www.tandfonline.com/journals/iebm20

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To cite this article: Dimitris J. Panagopoulos, Roman Litovsky & Kent Chamberlin (19 Apr 2026): Recording the extremely low frequency pulsations of wireless communication electromagnetic fields, Electromagnetic Biology and Medicine, DOI: 10.1080/15368378.2026.2654072

To link to this article: https://doi.org/10.1080/15368378.2026.2654072

Published online: 19 Apr 2026.

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ELECTROMAGNETIC BIOLOGY AND MEDICINE
https://doi.org/10.1080/15368378.2026.2654072

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Recording the extremely low frequency pulsations of wireless communication electromagnetic fields

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ABSTRACT

All digital Wireless Communication (WC) electromagnetic field (EMF)/radiation (EMR) signals (from mobile/"smart" phones and corresponding base antennas, cordless domestic phones, Wireless Fidelity (Wi-Fi) routers, "Bluetooth" wireless connection among electronic devices, etc.) are emitted discontinuously, in the form of on/off pulses repeated at various Extremely Low Frequency (ELF) rates. Yet, many scientists ignore/underestimate these ELF pulsations, and characterize all WC emissions simply as Radio Frequency (RF)/Microwave (MW) signals. Here, we provide recordings of ELF pulsations with respect to time, emitted by the most common WC devices, specifically Wi-Fi router, 4th and 5th Generation (4G, 5G) mobile phones. We used a broadband antenna, connected to an RF spectrum analyzer (SA), calibrated the SA at the signal's carrier MW frequency and recorded the power of the final emitted RF/MW signal with respect to time. We recorded emissions at 10 ms, 100 ms, 1 s, and 2 s sweep times, capturing the pulses repeated at various ELF rates, clearly showing the ELF pulsing emissions from the WC devices. As in all real WC EMF signals emitted by commercially available devices and corresponding antennas, there is intense variability in the amplitude, shape, duration, and repetition frequency of the pulses. The present study, in combination with the Ion Forced Oscillation and Voltage-Gated Ion Channel (IFO-VGIC) mechanism of non-thermal EMF-bioeffects, imply that the non-thermal biological and health effects of WC EMFs are induced by the ELF pulsation, modulation and variability, and not by the standalone (non-modulated) RF carrier wave EMFs which can produce only heating.

PLAIN LANGUAGE SUMMARY

Electromagnetic fields/radiation (EMFs/EMR) emitted by digital wireless communication (WC) devices (mobile/"smart" phones, cordless domestic phones, Wireless Fidelity (Wi-Fi) routers for connection to the Internet, etc.) and corresponding base antennas, are usually referred to simply as Radio Frequency (RF: 300 kHz–300 GHz) EMFs/EMR. Yet, as we have repeatedly declared before, this reflects only one part of the reality. The other part is that the RF signals that carry the transmitted information (text, speech, music, images, video, etc.) are contained within on/off pulses which are emitted/repeated at various Extremely Low Frequency (ELF: 3–3000 Hz) rates. Moreover, the RF signal within the pulses is modulated mostly by ELF EMFs, and the final signal contains random variability especially in amplitude which lies mainly in the Ultra-Low Frequency (ULF: 0–3 Hz) band. Therefore, all WC EMFs are a combination of high (RF) and low (ELF/ULF) frequencies. To record the ELF pulses, specific methodology and instrumentation are required. Here, we have recorded these pulses (as power with respect to time) from the most common WC EMFs/EMR, namely Wi-Fi, 4th, and 5th Generation (4G, 5G) WC EMFs/EMR. The present study, in combination with a widely accepted biophysical mechanism, the Ion Forced Oscillation and Voltage-Gated Ion Channel (IFO-VGIC) mechanism, of non-thermal EMF-bioeffects, imply that the non-thermal biological and health effects associated with exposure to WC EMFs are induced by the ELF/ULF pulsation, modulation and variability, and not by the standalone (non-modulated) RF carrier wave EMFs which can produce only heating at adequately high intensities rarely found in the environment.

ARTICLE HISTORY
Received 13 September 2025
Accepted 27 March 2026

KEYWORDS
Electromagnetic fields; wireless communications; radio frequency; microwaves; extremely low frequency; pulsing emissions; biological effects

Introduction

Many people, including scientists and health organizations, describe wireless communication (WC) electromagnetic field (EMF) emissions as purely Microwave (MW) (300 MHz–300 GHz) emissions within the wider Radio-Frequency (RF) band (300 kHz–300 GHz) of the electromagnetic (EM) spectrum, underestimating or even ignoring the importance of Extremely Low Frequency (ELF: 3–3000 Hz) impulsivity and modulation in them (ICNIRP 2020; Thielens et al. 2020; Beláčková et al. 2025;

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Foster et al. 2025). Several scientists have explicitly ignored the existence of ELF components of impulsivity and modulation, characterizing all types of WC EMFs as purely "RF" signals, stating that the modulation of WC EMFs is "noise-like", and cannot have any biological relevance (Foster et al. 2025). Yet, we have repeatedly declared that all digital WC EMF emissions (information-carrying EM waves) [Mobile Telephony (MT), i.e. mobile/"smart" phones and corresponding base antennas, cordless domestic (DECT: Digitally Enhanced Cordless Telecommunications) phones, "Wireless Fidelity" (Wi-Fi) routers for wireless Internet connection, "Bluetooth" wireless connection among electronic devices, etc.], consist of MW carrier waves modulated, mainly by ELF or Very Low Frequency (VLF: 3–30 kHz) signals, and included within on/off pulses (called "frames", "multi-frames", "sub-frames", etc.) repeated at various ELF rates. Moreover, all WC EMFs, apart from their variability in amplitude, frequency, waveform, etc., exhibit intense random variability in their final signals, especially in amplitude, with frequencies in the Ultra-Low Frequency (ULF: 0–3 Hz) band (Panagopoulos 2011, 2017, 2023; Panagopoulos et al. 2021, 2022, 2025). This becomes evident by observing the measured power density of any real-life WC signal by an RF field meter. In other words, all WC EMFs are a combination of MW and ELF/ULF/VLF EMFs.

The existence of low frequency EMF pulsations and modulation in all WC EMF emissions is of critical importance for the explanation of their biological and health impacts, as the vast majority of those impacts are non-thermal (they are not accompanied by any significant heating in the exposed living tissues), and there is no known mechanism to plausibly explain the induction of non-thermal biological or health effects by purely RF/MW EMFs. In fact, not only is there no known non-thermal mechanism for biological effects of RF EMFs, but also there is no RF emission by any living organism, neither by the natural environment. The so-called cosmic "microwaves" are not actually "microwaves" but infrared light shifted toward smaller frequencies due to the cosmic expansion and the Doppler effect (Panagopoulos et al. 2025). The only known biological effect of purely RF/MW EMFs is heating of the exposed biological tissues at adequately high intensities and frequencies, usually for RF intensities ≥ 1 mW/cm^2 (or ≥ 0.1 mW/cm^2 for subtle heating effects) and frequencies ≥ 1 GHz (Panagopoulos et al. 2021, 2022, 2025). But, there is such a non-thermal mechanism for ULF/ELF/VLF EMFs which is the Ion Forced Oscillation and Voltage-Gated Ion Channel (IFO-VGIC) mechanism (Panagopoulos et al. 2000, 2002, 2015, 2021, 2024, 2025), and explains all non-thermal effects reported in the literature. The IFO-VGIC mechanism finds that only low-frequency EMFs can produce non-thermal bioeffects, and the effects are proportional to field strength and inversely proportional to field frequency. Moreover, it finds that the effects increase with pulsed EMFs compared to corresponding non-pulsed (continuous-wave) of the same carrier frequency and field strength with that of the pulses.

Regardless of a mechanism, a great number of biological and health effects induced by WC EMFs have been documented, the most serious of which include oxidative stress (OS) induced within minutes of exposure, DNA damage, infertility, organic/neurodegenerative diseases, cancer, electro-hypersensitivity (EHS), etc. In the vast majority of cases, these effects are not accompanied by any significant heating of the exposed living tissues (De Iuliis et al. 2009a, 2009b; Yakymenko et al. 2016, 2018; Miller et al. 2018, 2019; Belpomme and Irigaray 2022; Jagetia 2022; Yakymenko and Tsybulin 2022a, 2022b; Panagopoulos 2023).

Moreover, since the pioneering experiments of Ross Adey, Carl Blackman and others in the 1970s and 1980s, it has been repeatedly documented that the strongest non-thermal biological and health effects are induced by modulated (especially in amplitude) or pulsed RF EMFs, and not by non-modulated continuous-wave carrier waves. The RF carrier waves are used in all WC EMFs to carry the information which is in the form of ELF/VLF variability (modulation) on the carrier wave (for review of studies having compared modulated versus non-modulated, and pulsed versus continuous-wave RF EMFs see Panagopoulos et al. 2022, 2025). For example, Frei et al. (1988) found that a 2.8 GHz RF EMF pulsed at 500 Hz was significantly more effective in increasing heart rate in rats than the corresponding non-pulsed EMF of the same power level and the same exposure duration. Huber et al. (2002) and Mohammed et al. (2013) found that exposure to 900 MHz RF EMF pulse-modulated with various ELF pulsations induced changes in the human and rat Electro-Encephalograms (EEG), respectively, while the corresponding non-pulsed EMF with the same exposure duration did not. Similarly, Franzellitti et al. (2010) found that a pulsing 1.8 GHz RF signal-induced DNA damage in cultured human trophoblast cells, while the corresponding continuous-wave signal with the same exposure duration was ineffective. In all cases, the reported effects were not accompanied by any significant tissue heating, apart from Frei et al. (1988) in which a very high power density (30–60 mW/cm^2) was applied, significantly exceeding the thermal limit (~1 mW/cm^2 for

frequencies of the order of 1 GHz) (Panagopoulos et al. 2022). The carrier waves alone, without modulation, pulsation, or other form of variability, usually do not produce effects other than heating, or at least, produce the weakest (if any) effect. Systematic attempts to produce non-thermal biological effects by RF carrier signals alone, without modulation or pulsation, were unsuccessful, and only thermal effects could be found by such exposures at higher power densities (Bush et al. 1981; Stensaas et al. 1981; Gandhi 1983; Furia et al. 1986). By contrast, standalone ELF EMFs induce non-thermal effects, alike, even though not necessarily identical to, the RF EMFs modulated or pulsed by the same ELFs (see references in Panagopoulos et al. 2022). As noted by Goldsworthy (2006), "radio waves can also give biological effects, but only if they are pulsed or amplitude-modulated at biologically active low frequencies".

Yet, this important knowledge has been largely ignored by the scientific community and the health authorities. As a result, those who promote the obsolete idea that anthropogenic EMFs cannot possibly induce any biological or health effects other than heating, such as a private organization called the International Commission on Non-Ionizing Radiation Protection (ICNIRP 2020), have succeeded to detract the attention of the scientific community from the fact that the non-thermal biological effects are induced by the low frequency (ULF/ELF/VLF) modulation-pulsation-variability that necessarily exist in all WC/RF EMF emissions, and not by the purely RF/MW carrier wave components of the WC EMFs.

Very few previous studies have recorded ELF pulsations from WC devices/antennas, mostly from Global System for Mobile Telecommunications (GSM) (or 2 G), Universal Mobile Telecommunications System (UMTS) (or 3 G), DECT, and certain other WC EMF sources (Pedersen 1997; Zwamborn et al. 2003; Zhou et al. 2010; Pirard and Vatovez n.d.). An early study that recorded such pulsations from GSM and DECT phones was by Pedersen (1997). This important study captured the pulsations with respect to time, and provided the corresponding ELF spectra in the frequency domain. Pedersen used "a low frequency spectrum analyzer to obtain the frequency spectra of the ELF magnetic fields and a storage oscilloscope for the time domain measurements".

In Panagopoulos et al. (2022), we provided figures of pulsations of GSM (2 G), UMTS (3 G), Wi-Fi, DECT, and UMTS Long Term Evolution (UMTS LTE or simply LTE) (or 4 G), collected from available publications. The purpose of the present study was to record the basic ELF pulsations with respect to time, from a commercially available Wi-Fi router, as well as LTE (4 G) and New Radio (NR) (5 G) from a commercially available "smart" phone.

Materials and methods

To record the ELF pulsations from WC signals, specific methodology and instrumentation are required. We used an Ultra-Wideband (UWB) spiral antenna (510 MHz–10 GHz), connected to an Agilent RF spectrum analyzer (SA) (Agilent Technologies, Inc. USA). We placed the antenna close to the operating WC EMF source which was a) a Wi-Fi router (TP-Link, model WiFi-6, China, output power lowest) during video streaming of a connected device far away from the router, or b) a "smart" phone (4 G/5 G Apple iPhone 15) during a call with another phone located far away from the iPhone. The UWB spiral antenna was ~1 m from the router, or ~10 cm from the iPhone, respectively, during the measurements. Figure S shows the setup with the "smart" phone, the UWB spiral antenna at 10 cm distance, and the cable connecting the antenna with the SA.

We calibrated the SA at each signal's carrier MW frequency (~2.45 GHz for Wi-Fi, ~840 MHz for LTE 4 G, and ~1.876 GHz for NR 5 G), selected wide enough frequency bandwidth (BW), and set the SA into "zero span" mode, making it work as an oscilloscope displaying the emitted power with respect to time. [The zero span mode fixes the SA to a narrow frequency band around the selected frequency, making it display the

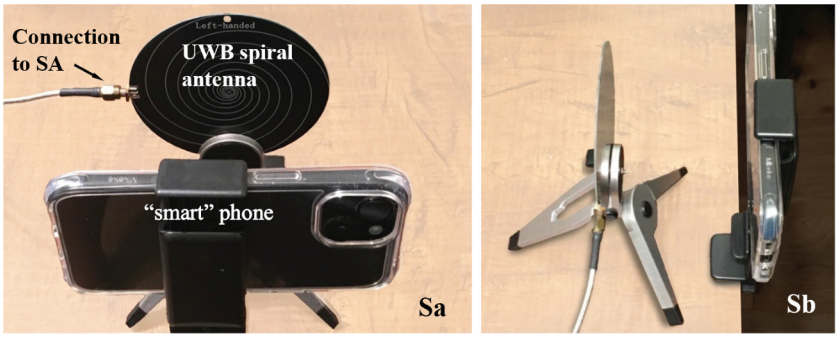


Figure S. Measurement setup with "smart" phone and RF spiral antenna at 10 cm connected to the SA, as seen from two different angles.

signal's amplitude/power variations versus time, instead of displaying power versus frequency.]

In the menu of the iPhone we selected LTE (4G) or NR (5G) connection. Internet access (Wi-Fi, data) and Bluetooth modes of the iPhone as well as the room Wi-Fi router were turned off during the measurement of the 4G/5G emissions. Similarly, the iPhone was turned off during the measurements of the Wi-Fi router emissions. We applied different sweep times (10 ms, 100 ms, 200 ms, 1 s, 2 s) corresponding to the nominal repetition frequencies of the various pulsations (10 Hz for Wi-Fi, 100 Hz ("frames"), 1000 Hz ("sub-frames") and possible lower repetition frequencies ("multi-frames") for LTE (4 G) and NR (5 G), and varied the trigger level (mostly around −10 dBm) in order to optimally capture the pulsations at the various repetition frequencies. For the recording of the background (control) emissions, we tuned the SA at the carrier frequency of each source, turned the source (Wi-Fi router or iPhone) off, selected maximum BW at the SA (~3 MHz), zero span, and 1 s sweep time.

It is known that the ELF pulsations of all WC EMFs are very variable in repetition frequency and intensity, and this is one reason why they are so much bioactive (Panagopoulos et al. 2022, 2025). The nominal pulse repetition frequencies for "frames", "sub-frames", "multi-frames", etc. are only approximate, depending on the type and amount of information being transmitted, number of subscribers using the network, and many other factors. We kept the measurement conditions as stable as possible but made no particular attempt to control the variability due to the variable other parameters. At least 10 recordings were acquired for each specific condition/measurement, and we chose the ones that depicted the pulses as clearly as possible. No EMF-shielding was used during the measurements.

The intention of the present study was to qualitatively show the ELF pulsations with respect to time and approximately estimate their frequencies. It was not our purpose to measure the intensity (RF power density) of the pulsations, as this can be easily done by use of an RF field meter. Similarly, it was not our purpose to get frequency spectra of the recorded pulsations as this is subject for a separate study. The power (P) amplitudes of the pulsations as recorded by the SA are shown in decibel milliwatts (dBm) and may be converted to mW according to the formula: P (dBm) = 10 × log P (mW).

Power (P) can be converted to power density (J) by taking into account the antenna gain (G) at the radiation wavelength, but such calculations transcend the scope of this study. The highest peak emission recorded in our measurements did not exceed ~40 μW/cm^2 with LTE (at 10 cm distance from the iPhone), which is ~47.5 times lower than the latest ICNIRP (2020) limit (averaged over 6 min) for public exposure at 840 MHz (1900 μW/cm^2).

Results

The results of our recordings are shown below. The recordings depict the final modulated signal emitted by the WC devices (Wi-Fi router, 4G/5G iPhone) captured with respect to time. The figures in the SA show the various ELF pulsations (emitted power with respect to time) from the three different EMF sources [Wi-Fi, LTE (4G), and NR (5G)]. The frequencies of the various pulsations can be deduced from the sweep time in each figure.

Wi-Fi pulsations emitted by a router for wireless connection to Internet

Figure 1a shows the recording of the background noise (control recording) for Wi-Fi with all RF EMF sources turned off. The power of the recorded background noise is ~ −51 dBm or ~$10^{-5.1}$ mW. Figures 1b,c show Wi-Fi

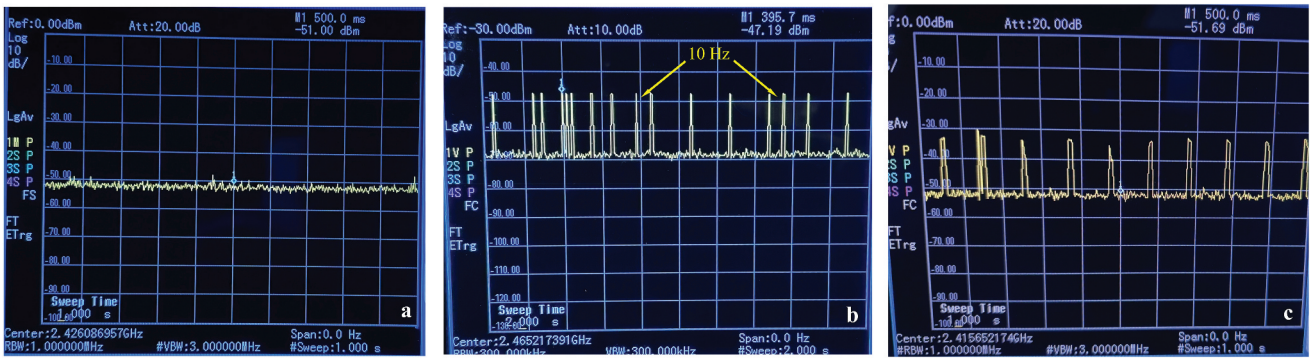


Figure 1. (a) Background (control) recording for Wi-Fi (2.45 GHz) with router and all RF sources turned off. Center frequency: ~2.43 GHz. Sweep time: 1 s. (b): ~5–20 Hz pulses from the Wi-Fi router. Arrows indicate pulses with ~10 Hz repetition. Center frequency: ~2.46 GHz. Sweep time: 2 s. (c): Pulses with ~10 Hz repetition frequency emitted by the Wi-Fi router. Center frequency: ~2.42 GHz. Sweep time: 1 s.

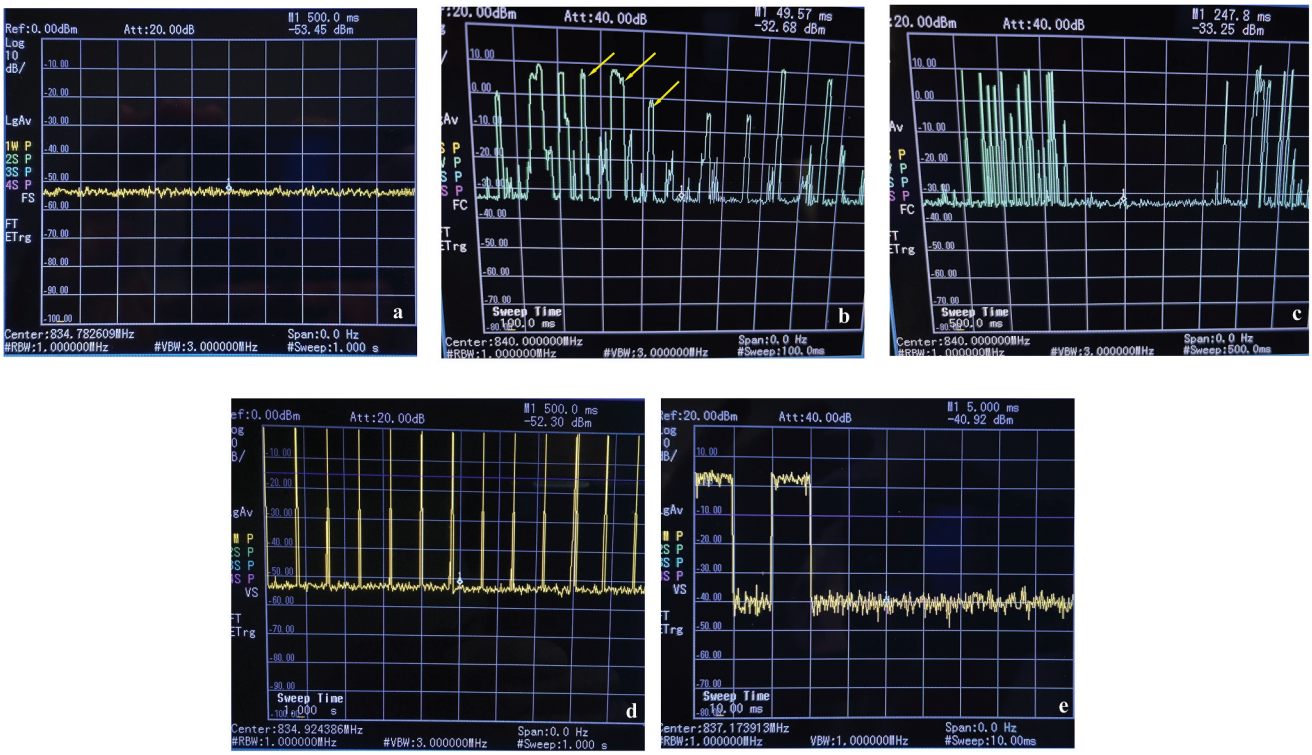


Figure 2. (a): Background (control) recording for LTE (4 G) with "smart" phone and other RF sources turned off. Center frequency: ~835 MHz. Sweep time: 1 s. (b): LTE (4 G) ~100 Hz pulses ("frames") of ~2–10 ms duration each and variable amplitudes (arrows), emitted by the "smart" phone. Center frequency: 840 MHz. Sweep time: 100 ms. (c): LTE (4 G) pulses ("frames") of ~5 ms duration each, with ~100 Hz repetition frequency from the "smart" phone, emitted in bursts of ~100 ms duration ("multi-frames") repeated at a rate of ~3 Hz. Center frequency: 840 MHz. Sweep time: 500 ms. (d): LTE (4 G) pulses, probably for synchronization or reference purposes, repeated at a rate of ~12.5 Hz. Center frequency: ~835 MHz. Sweep time: 1 s. (e): LTE (4 G) sub-frames of ~1 ms duration each, repeated at a rate of ~500 Hz. Center frequency: ~837 MHz. Sweep time: 10 ms.

pulsations (also referred to as "beacons") at a repetition frequency close to 10 Hz, and power level ~20 dB above the background. While in Figure 1b the repetition frequency of the Wi-Fi pulsations is more variable (in the range 5–20 Hz), even though always remaining close to 10 Hz as in Zhou et al. (2010) who were probably the first to record Wi-Fi pulsations, in Figure 1c those pulsations are quite steady close to 10 Hz. The modulated RF carrier signal (~2.45 GHz) is contained within these pulses.

LTE (4 G) pulsations emitted by a "smart" phone during a phone call with another phone

Figure 2a shows the background noise (control recording) for LTE (4G) (center frequency around 840 MHz) with all RF EMF sources turned off. The power of the recorded background noise is ~ −53 dBm or ~$10^{-5.3}$ mW. Figure 2b, shows LTE (4G) 100 Hz pulsations ("frames") of power level ~40 dB above background, emitted by the iPhone during a phone call with another mobile phone. All other functions such as Internet accessibility (Wi-Fi, data), and Bluetooth, were turned off. Figure 2c shows the 100 Hz frames emitted in groups ("multi-frames") of approximately 100 ms duration, with approximately 3 Hz repetition frequency. Figure 2d shows single pulses of uniform amplitude and duration and power level ~53 dB above background, probably for synchronization or reference purposes repeated at a rate of ~12.5 Hz. Finally, Figure 2e shows LTE sub-frames, of power level ~43 dB above background, repeated at a rate of ~500 Hz. (each sub-frame of 1 ms duration consists of 2 slots of 0.5 ms duration) (Sesia et al. 2011). The modulated carrier RF signal is within such slots/sub-frames. The sub-frames are included within the frames, and the frames are emitted in groups of multi-frames.

NR (5G) pulsations emitted by a "smart" phone during a phone call with another phone

Figure 3a shows the background (control) noise for NR (5G) (center frequency 1.878 GHz) with all RF EMF sources turned off. The power of the recorded background noise is ~ −52 dBm or ~$10^{-5.2}$ mW. Figure 3b shows 100 Hz pulsations (frames) of ~2–10 ms duration

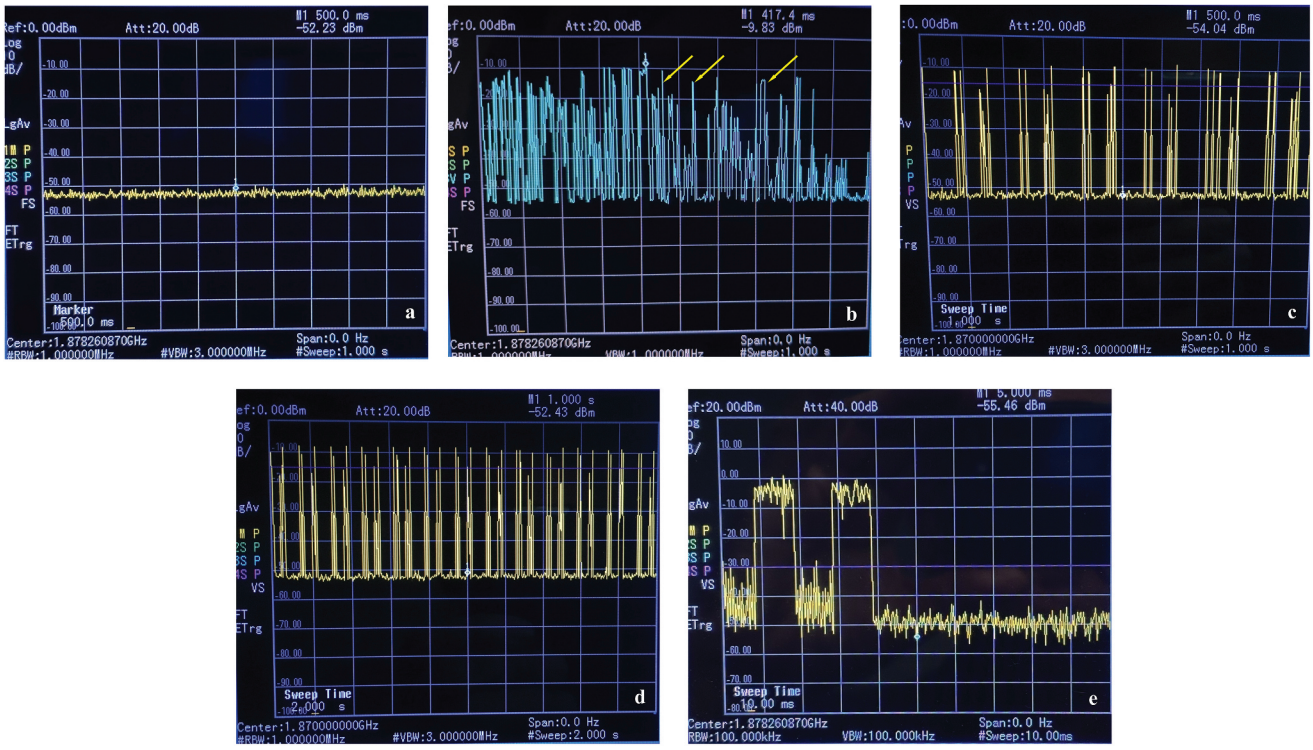


Figure 3. (a): Background (control) recording for NR (5 G) with "smart" phone and other RF sources turned off. Center frequency: ~1.878 GHz. Sweep time: 1 s. (b): NR (5 G) ~100 Hz pulses (frames) of (up to) 10 ms duration each (arrows), from the "smart" phone during an active phone call with another phone. Center frequency: ~1.878 GHz. Sweep time: 1 s. (c): NR (5 G) groups of 2–3 frames, repeated at ~13 Hz. Center frequency: ~1.87 GHz. Sweep time: 1 s. (d): A similar NR (5 G) emission pattern as in Figure 3(c), with groups of 2–3 frames repeated at ~13 Hz. Center frequency: ~1.87 GHz. Sweep time: 2 s. (e): NR (5 G) sub-frames of ~1 ms duration each, repeated at ~500 Hz. Center frequency: ~1.878 GHz. Sweep time: 10 ms.

Table 1. Summary of findings on the parameters of ELF pulsations of WC EMFs.

WC EMF type	Carrier frequency (RF)	Pulse type and repetition frequency (ELF)	Pulse width	Power amplitude above background	Figure
Wi-Fi	~2.45 GHz	~10 Hz (5–20 Hz)	~20 ms	~20 dB	1b, 1c
LTE (4G)	835–840 MHz	~100 Hz (frames)	2–10 ms	~40 dB	2b
		~3 Hz (multi-frames)	~100 ms	~40 dB	2c
		~500 Hz (sub-frames)	~1 ms	~43 dB	2e
		~12.5 Hz synchronization pulses	~10 ms	~53 dB	2d
NR (5G)	1.870–1.878 GHz	~100 Hz (frames)	2–10 ms	~40 dB	3b
		~13 Hz (groups of frames)	20–30 ms	~40 dB	3c, 3d
		~500 Hz (sub-frames)	~1 ms	~45 dB	3e

each and power level ~40 dB above background, emitted by the same iPhone during an active phone call with another mobile phone. All other functions such as Internet accessibility (Wi-Fi, data), Bluetooth, etc., were turned off. While in LTE function the group of frames (multi-frame) had a duration of ~100 ms (Figure 2b) the corresponding duration in NR (5G) function (at least as captured in Figure 3b) lasts for ~1 s. Figure 3c shows groups of 2–3 frames repeated at a rate of ~13 Hz. Figure 3d shows a similar emission pattern as Figure 3c in 2 s sweep time. Figure 3e shows two NR (5G) sub-frames of ~1 ms duration each and power level ~45 dB above background, with a repetition rate ~500 Hz. Those sub-frames bear the modulated RF carrier wave. Up to 10 sub-frames are included within one frame.

The parameters of the various pulsations as recorded in our study from the three types of WC EMFs, i.e. Wi-Fi, LTE (4G), and NR (5G), are summarized in Table 1.

Discussion

We have recorded Wi-Fi, LTE (4G) and NR (5G) WC signals (signal amplitude with respect to time) for various sweep times, demonstrating what we have repeatedly declared before (Panagopoulos et al. 2021, 2022, 2025): That all digital WC EMFs from devices and

corresponding antennas are emitted discontinuously in the form of on/off pulses that contain the modulated RF signal, and repeated at various ELF rates. The recordings of the pulsations emitted by real-life WC devices fully verify a) the existence of pulsations repeated at various ELF rates, and b) that all real-life WC EMFs and specifically the pulsations themselves are highly variable in amplitude, repetition frequency, duration, shape, etc. The intense low-frequency (ULF/ELF/VLF) variability of all real-life WC EMFs, in combination with the fact that they are fully polarized and coherent, makes them particularly adversely bioactive, as the living organisms cannot adapt to a highly variable polarized and coherent stressor (Panagopoulos et al. 2015, 2025). Even though we captured the various pulsations by recording the RF final signal in the time domain, the same pulsations can also be recorded as ELF magnetic field pulsations by use of ELF SA close to the devices as by Pedersen (1997). This can be the subject of a next study.

Apart from the UWB spiral antenna, we also tested for the same measurements a Vivaldi horn RF antenna (850 MHz–11 GHz). The results were very similar to those with the UWB spiral antenna, showing that the recorded pulsations of the WC devices do not depend on antenna type, once the carrier frequency is within the antenna's range.

Apart from the inherent variability of the WC real-life signals, an additional reason why some of the recorded pulses have lower amplitude, by about 1–10 dB, than the majority of the pulses, is related to the SA BW. The Agilent RF SA that we used has a resolution bandwidth (RBW) of less than 3 MHz. The instantaneous bandwidth (IBW) is typically larger than the RBW. The LTE (4G) and NR (5G) signals have their channel bandwidth of about 20 MHz. Therefore, if during the scan the signal changes its carrier frequency by more than ±1.5 MHz it will be displayed with less amplitude as it goes out of the SA RBW in zero span mode. This did not happen too often during our measurements, but during scans longer than 100 ms we can see many pulses at a lower amplitude. While most commercially available SA have the highest RBW of less than 5 MHz, the described weakness would be minimized by use of a "Real Time SA" with IBW of 20 MHz or higher.

The sub-frames in LTE (4G) and NR (5G) are reported to nominally have a repetition frequency at 1000 Hz (Sesia et al. 2011; Dahlman et al. 2018). Yet, we captured them having a repetition frequency ~500 Hz (Figures 2e, 3e). This fact probably shows that not all available sub-frames are always emitted, but only those required for the amount of information that is to be transmitted. In other words, the nominal sub-frame, frame, and multi-frame repetition frequencies represent the maximal emission rates and not those that are actually transmitted, which further explains the observed signal variability.

The present study, in combination with the IFO-VGIC mechanism of non-thermal EMF bioeffects (Panagopoulos et al. 2000, 2002, 2015, 2021, 2024, 2025) imply that the non-thermal biological and health effects of WC EMFs (OS, DNA/cellular damage, EHS, infertility, organic diseases, cancer, etc.), are induced by the ELF/ULF/VLF EMFs of pulsation, modulation and variability, and not by the standalone (non-modulated) RF carrier wave EMFs which can actually produce only heating at adequately high intensities and frequencies rarely found in the environment (Panagopoulos et al. 2022). In other words, a) there are ELF pulsations-modulation-variability EMFs in all types of WC/RF EMFs and b) there is a widely accepted biophysical mechanism that explains the non-thermal biological effects of ULF/ELF/VLF EMFs, but there is no corresponding mechanism to explain such effects from purely (non-modulated) RF EMFs.

We should emphasize that the VGICs which are the natural and very sensitive EMF-sensors, abundant in the membranes of all cells in all living organisms, do not respond (by opening/closing) to the normal membrane voltage (~100 mV), but only to low frequency voltage changes of 30–100 mV in the membrane voltage. This is why they are expected to respond only to modulated RF EMFs and not to invariable/non-modulated carrier wave RF EMFs (Panagopoulos et al. 2024, 2025). This means that it makes no difference for the VGICs (and the living organisms) whether the low frequency components of WC EMFs exist independently of the RF signal (which we believe is the case), or they are only the result of modulation. In other words, in the absence of modulation/impulsivity, the RF EMFs cannot induce effects because the VGICs do not respond to an invariable applied EMF or to high frequency (RF) non-modulated carrier waves, but only respond to low frequency (ULF/ELF/VLF) field changes (which normally occur with membrane depolarizations) (Panagopoulos et al. 2025). This comes from the plethora of information on the structure and function of the VGICs, and shown by mathematical equations in the IFO-VGIC theory for the minimum force on the VGIC voltage-sensors required to gate (open/close) a VGIC. The forces on the voltage-sensors are normally exerted by membrane voltage changes/depolarizations but may also be exerted by mobile ions passing through or bound in specific ion-binding sites within VGICs and forced to oscillate by an applied low frequency (ULF/ELF/VLF) EMF (Panagopoulos et al. 2021, 2024, 2025). Moreover, this is supported by experimental studies showing effects by either standalone ELF EMFs or ELF

modulation of RF signals, even though the effects may not necessarily be identical in the two cases. For example, Bawin and Adey (1976) found that the ELF sinusoidal signals previously used to modulate an RF carrier EMF (Bawin et al. 1975, 1978), induced alone (without the RF carrier) alterations in Ca^{2+} concentration in chicken and cat brain cells as did the modulated RF EMF, while the RF carrier alone (non-modulated) was ineffective. Azanza et al. (2002) found that the ELF pulsations employed in 2G MT at 8.3 and 217 Hz could, by themselves (without the carrier RF signal), induce changes in the spontaneous bioelectric activity of neurons (see more in Panagopoulos et al. 2022, 2025).

Thus, we do not distinguish the standalone ELF EMFs over the ELF modulation of RF signals, even though this topic needs to be further investigated and there is still much to learn on this. Specifically, more studies should be carried out comparing the biological effects between ELF-modulated RF EMFs and the corresponding standalone ELF EMFs. Moreover, a new methodology should be developed to measure the ELF pulsations of WC EMFs with ELF SA and field meters.

Similarly, we do not distinguish ELF EMFs within tissues from the incident ELF EMFs because ELF EMFs are significantly penetrating in living tissue. Even though electric fields are less penetrating than magnetic fields in any material including living tissue, it is known that isolated tissues respond to externally applied pulsed or sinusoidal ELF electric fields at very low thresholds ($\sim 10^{-3}$ V/m) similar to those predicted by the IFO-VGIC mechanism (McLeod et al. 1987; Cleary et al. 1988; Lee et al. 1993). This shows that ELF electric (and magnetic) fields penetrate living tissue enough to induce effects, even at very low field intensities. Moreover, skin cells, nerve terminals, eyes, and organs close to the body surface such as the brain, heart, testes, etc., are directly exposed to the externally applied EMFs.

Even though we recognize it is unlikely that the small sizes of WC EMF antennas allow them to transmit ELF signals directly, the impulsivity transmitted by them at various ELF rates is delivered to the exposed biological tissues and is shown to have a significant biological impact on them.

The present study clearly shows the existence of ELF pulsations in modern digital WC EMFs, which, in combination with the IFO-VGIC mechanism, fully explain and further validate the non-thermal biological and health effects reported in the EMF-bioeffects literature to be induced by various types of WC EMFs. An important application of the present research should be that the scientific community, the health authorities, and the industry, should stop treating WC EMFs as standalone RF EMFs with thermal-only effects, but should start measuring their inherent ELF pulsations, and considering the corresponding non-thermal biological effects. Especially, the health authorities should revise their guidelines to account for the non-thermal biological and health effects due to the ELF pulsations which occur at RF power densities much lower than those inducing thermal effects.

In conclusion, the more we know about the physical characteristics and waveforms of the various EMFs and the mechanism of induced biological effects, the more we understand about these effects and how to control them. We hope the present study effectively contributes toward a more realistic understanding, recording, and quantization of the physical properties, and consequently, a more relevant evaluation and understanding of the non-thermal effects and health risks associated with WC EMF exposures.

Acknowledgements

DJP designed the study and wrote the paper. RL performed all EMF measurements. KC reviewed and evaluated all data. All authors approved the final manuscript.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

Funding

No funding was received for this work.

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