# Antenna-User Interaction in MIMO-Enabled Laptops

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**Abstract.** *The operation of wireless personal communication terminals very close to the user inherently faces the problem of electromagnetic (EM) coupling between the device and the biological tissues. In this paper the effects of the electromagnetic antenna-human interaction is studied for a laptop MIMO antenna system, where four integrated antenna elements can operate simultaneously. Two points of view are considered: antenna performance and EM dosimetry. The first one addresses not only the degradation of the antenna performance but includes also the effect of the human proximity on the antenna characteristics, namely scattering matrix, Total Active Reflection Coefficient (TARC), radiation efficiency and envelope correlation between port signals. The exposure of the human tissues to EM radiation is expressed in terms of Specific Absorption Rate (SAR). These characteristics are evaluated as a function of the array excitation scheme (including phased array approach and MIMO-like signaling) and compared to simple scenarios where all the power is radiated only by one antenna element.*

## Keywords

Laptop antennas, MIMO antenna systems, TARC, SAR, EM dosimetry.

## 1. Introduction

In wireless personal communications the mobile terminals inherently operate very close to the user. The coupling between the antenna and the human, often located in the antenna near-field zone, affects the antenna parameters and causes microwave energy absorption in the user's body. In the beginning of the 90s, when handsets became widely popular, coupling between antennas and the user's head has been investigated [1]. Nowadays, as the variety of portable units equipped with wireless interfaces are growing, the antenna-human interaction should be thoroughly investigated in a wide range of scenarios. Moreover, use of new Multiple-Input Multiple-Output (MIMO) techniques [2] requires the simultaneous operation of several terminal antenna elements which affects the way the terminal interacts with the human.

In the present paper the effects of electromagnetic interaction between a laptop integrated MIMO antenna system operating in the popular ISM 2.4 GHz band (described in Section 2) and the user (human model described in Section 3) are studied numerically with the aid of CST Microwave Studio software tool [3]. The human effects on the antenna performance and the antenna operation effect on the human are addressed in Sections 4 and 5, respectively. Simulation results obtained with CST Microwave Studio software tool have been validated by experimental results in many and varied printed antenna configurations [4-8]. Therefore, although only CST simulation results are presented the authors have confidence in their validity.

## 2. MIMO Antenna System of Back-to-Back E-Shaped Patches

### 2.1 Back-to-Back E-Shaped Patch Element

The back-to-back E-shaped patch element has been introduced in [4]. This novel element consists of two E-shaped sections (printed on a dielectric substrate) and a connecting strip, constituting a continuous patch conformably embracing the ground plane edge. The detailed antenna geometry and the inverted microstrip feeding line are presented in [5]. In the numerical simulations the metallic parts are modeled as thin PEC layers whereas the dielectric is assumed to be lossless. The antenna operates in the ISM 2.4 GHz and UNII 5.2 GHz bands and despite integration into the electrically large laptop, assures almost omnidirectional total gain horizontal plane pattern [5]. Due to limited computation resources all simulations including the presence of the electrically large human model (see Section 3) are limited to 2.4 GHz.

### 2.2 4 Element Linear Array Integrated in the Laptop

A four-element linear array of back-to-back E-shaped patches (Fig. 1) has been introduced in [6]. The radiators are integrated along the top screen rim with spacing D = 81 mm, which corresponds to 0.66λ (@2.44 GHz) as shown in Fig. 2a. In the numerical simulations the laptop screen has been modeled as a PEC box of dimensions 295×225×1 [mm$^3$] mounted perpendicularly to a 295×260×25 [mm$^3$] PEC box representing the keyboard structure. An antenna prototype has been built and integrated into a Toshiba Satellite chassis (Fig. 1). The good agreement obtained between numerical simulations and experimental results has validated the simulation model used [6]. The integrated array has also been measured with the aid of a true-MIMO test bed in the whole range of multipath indoor scenarios [7] and has been shown to be MIMO-capacity preserving. However, the analysis presented in [6] and [7] does not consider the presence of the laptop operator.

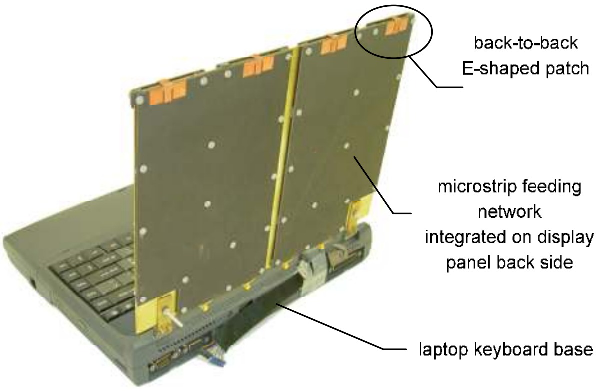

**Fig. 1.** Laptop antenna array prototype.

## 3. Human Model

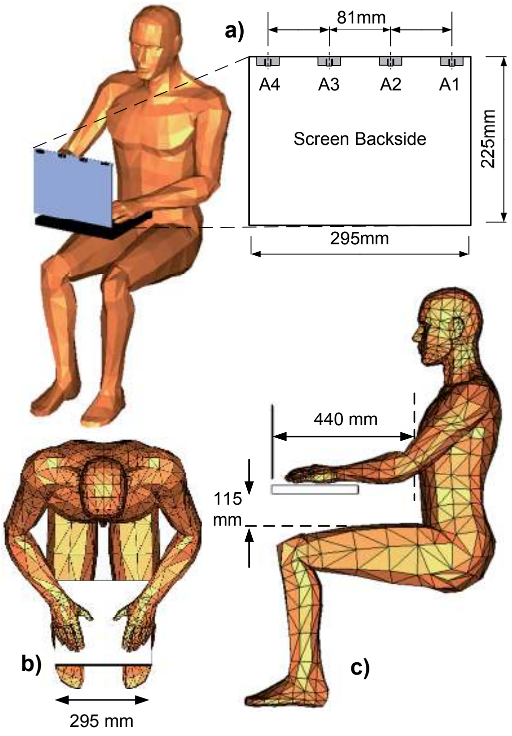

**Fig. 2.** Laptop with integrated antenna array in the presence of the user.

In this work the operation of an antenna array integrated into a laptop terminal, in the presence of the operator, is investigated. A human body model based on an anatomical mannequin, corresponding to a 177 cm tall, 72 kg weight male, generated by Poser™ software tool has been used [9]. As shown in Fig. 2, a typical typing posture [10] has been introduced. Since only the external shapes and sizes are used, the generated model is homogeneous. Dielectric material of relative permittivity $\varepsilon_r = 45.6$, dielectric loss tangent $\tan\delta = 0.23$ and mass density $\rho = 1000$ kg/m$^3$ has been used to simulate the human biological tissue at 2.44 GHz. These values correspond to the averaged properties of 85% of muscle and 15% of fat which can be considered representative of a common healthy male [11].

## 4. User Effects on Array Performance

The effects of the human presence on a single back-to-back E-shaped antenna element, integrated in different laptop locations, have already been described in [10]. This section is focused on the array parameters.

### 4.1 Scattering Matrix

The comparison of selected computed scattering matrix elements between standalone and typing user scenarios is presented in Fig. 3 (first row). Very little effect of the human on the scattering matrix is visible. In the presence of the operator, antenna elements couple not only through the antenna structure but also through the wave reflected in the human tissue. For a given frequency the user reflected wave may have constructive or destructive character, that is, may increase or decrease the mutual coupling and correlation (see Section 4.4). This effect is more pronounced for sparsely spaced elements ($S_{31}$ and $S_{41}$) where through-structure coupling is smaller.

### 4.2 TARC and Radiation Efficiency

In order to evaluate the array return loss under MIMO-like signaling conditions the Total Active Reflection Coefficient (TARC) has been computed from the computed S matrix according to [12]. Each of the 100 TARC curves (Fig. 3, second row) represents the simulated input reflection coefficient for excitation with constant amplitude but a different random phase which mimics MIMO signaling.

For both the analyzed scenarios (without user and with user) the TARC results are very similar within the ISM 2.4 GHz band. In some excitation schemes the human effect is more visible, but the envelope TARC is practically not changed (the human presence causes up to 0.4 dB difference in the band of interest). It should be stressed that the method used to calculate TARC accounts only for losses caused by reflection and coupling through the antenna ports (does not include losses in the antenna, laptop and user).

In the numerical simulations the antenna elements and laptop housing is composed solely of PEC and lossless dielectrics, therefore the entire power absorbed by the system $P_{abs}$ is absorbed only by the human body. The radiation efficiency of the laptop-user system is defined as

$$\eta_r = \frac{P_{rad}}{P_{rad} + P_{abs}} = \frac{P_{rad}}{P_{acc}} \qquad (1)$$

where $P_{rad}$ is the power radiated to the far-field region, $P_{acc}$ is the power accepted by the array and $P_{abs}$ is the power absorbed by the human body. As defined, this parameter does not take into account the array input mismatch and inter-port coupling losses, already considered in TARC.

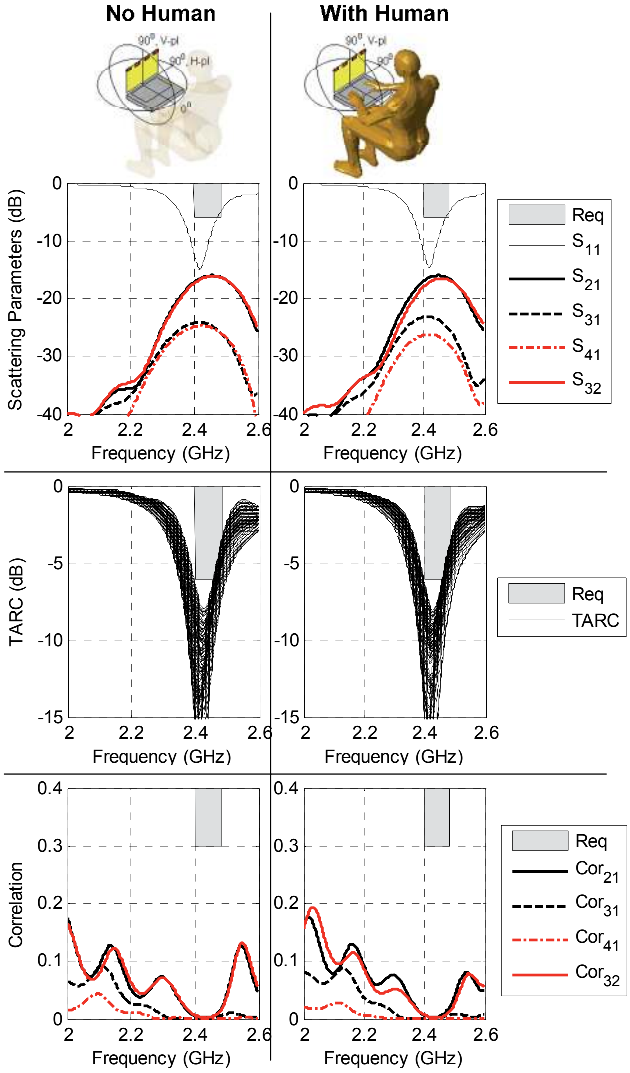

**Fig. 3.** Human effects on array performance: scattering matrix, TARC and envelope correlation.

The antenna radiation efficiency calculated according to (1) is presented in Fig. 4 for different excitation schemes including: single-port excitation (Fig. 4a, columns 1-3), multi-port excitations in phased array fashion (Fig. 4a, columns 4-6) and multi-port excitations in MIMO-like fashion (excitation vector with constant amplitudes and random phases, Fig. 4b). It can be seen that the radiation efficiency depends on the excitation scheme. The array far-field radiation pattern is a function of the excitation vector (see Section 4.3); therefore the excitation also affects the human illumination (see Section 5) and the resulting losses in the human tissue. The lowest radiation efficiency is obtained for a phased-array excitation that leads to strong illumination of the human body by an array main beam (see broadside and ~15 degrees from broadside scenarios). For a ~30 degrees from broadside scenario the array main beam is already away from the user's left arm which results in a small efficiency improvement. For all the analyzed scenarios, including MIMO-like signaling schemes, the radiation efficiency is above 80%. It is important to note that in the presence of the user different excitations can change the radiation efficiency by as much as 10%.

## 4.3 Far-Field Radiation Pattern

As mentioned in Section 4.2, the array far-field pattern is a function of the excitation vector (compare patterns in Fig. 4). However, in all configurations the human effect on radiation pattern has the same character, as already analyzed for a single radiator [10], including mainly shadowing of the backward radiation and weak reflection causing small ripple in the entire pattern. For all the analyzed scenarios the keyboard effect [5] is also well visible in the V-plane patterns by enhanced radiation in the elevation range $50^0$-$70^0$.

## 4.4 Envelope Correlation

Mutual coupling contributes to correlation of received signals in antenna ports A and B. Assuming a propagation scenario where there is an incident field with uniform distribution the envelope correlation can be obtained from the S parameters [13] of the antenna system as

$$\rho_e = \frac{\left|S_{AA}^* S_{AB} + S_{BA}^* S_{BB}\right|^2}{\left(1-\left|S_{AA}\right|^2-\left|S_{BA}\right|^2\right)\left(1-\left|S_{BB}\right|^2-\left|S_{AB}\right|^2\right)} . \qquad (2)$$

As it can be verified in Fig. 3 (third row), the presence of the user has very little effect on the envelope correlation. It is also important to stress that the correlation between all antenna ports is very low. It is below 0.1 in the whole frequency range of interest.

# 5. Array Effects on User

The electromagnetic energy absorbed by the human body can potentially represent a health risk, therefore it should be minimized. The maximum exposure of human tissues to electromagnetic fields has been defined in terms of Specific Absorption Rate (SAR). In Europe the maximum allowed SAR (averaged over 10 g of tissue) is 2 W/kg [14].

The laptop user SAR for all the investigated scenarios has been evaluated considering an array accepted power $P_{acc} = 1$ W (peak). In multi-port excitation scenarios each element accepts 0.25 W (peak). Fig. 4 presents the 10 g averaged SAR distribution on the human body surface, and the peak 3D SAR values. The highest peak SAR values occur in the user hands and, for all the analyzed scenarios (including 20 different random MIMO-like excitation schemes), it is always below 0.5 W/kg, which is far from the safety limits of the European standards.

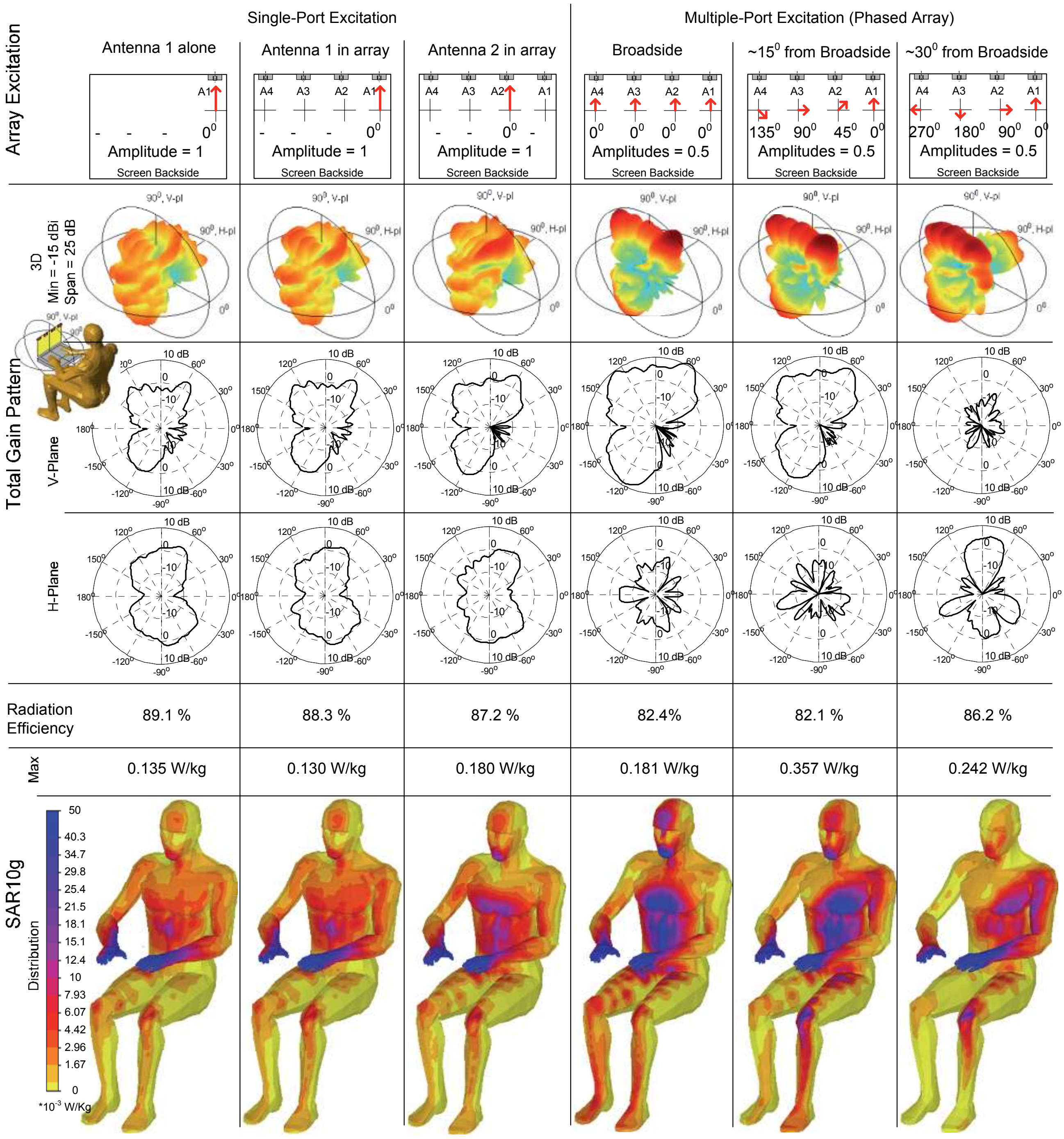

**Fig. 4a.** User effects on the array far-field radiation pattern and SAR distribution as a function of array excitation (continued on Fig. 4b).

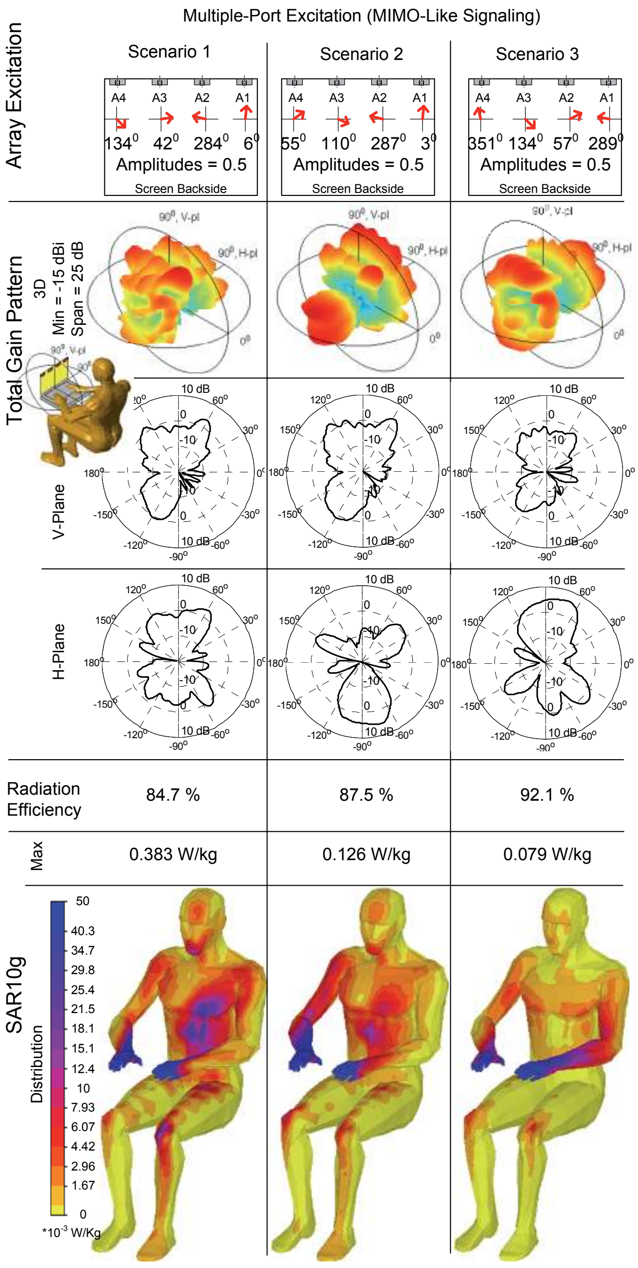

**Fig. 4b.** User effects on the array far-field radiation pattern and SAR distribution as a function of array excitation (continuation of Fig. 4a).

The distribution of SAR in the human body depends on the excitation vector. The strongest SAR concentration occurs in the torso area for phased array scenarios, where a distinct main beam is formed. Although the user torso is not in the far-field region (approximately 1.4 m @ 2.4 GHz) there is a clear dependence of the SAR distribution on the beam tilting (see Section 4.3).

It is important to notice that the given SAR values are normalized to 1W peak array output power, while typically a WLAN antenna system radiates only about 10 mW. Other wireless laptop interfaces, like cellular modems or WiMAX radios, can work with much higher power levels. Moreover, the properties of the human tissues are frequency dependent. Finally, the simplified homogenous human model does not take into account different electromagnetic properties of real human tissues and consequently provides only an estimation of the absorbed energy.

## 6. Conclusions

In this paper the effects of electromagnetic interaction between the human body and a laptop integrated MIMO antenna array operating in the ISM 2.4 GHz band have been studied numerically from the viewpoint of array performance and EM dosimetry. The first part addressed the degradation of array performance as well as the effect of the human proximity on the array characteristics, namely scattering matrix, total efficiency, Total Active Reflection Coefficient (TARC) and envelope correlation. The exposure of the human tissues to EM radiation has been expressed in terms of Specific Absorption Rate (SAR). All those characteristics have been evaluated as a function of the array excitation scheme (including phased array approach and MIMO-like signaling) and compared to simple scenarios where all the power is radiated by only one antenna element.

It has been found that the human presence has a very small effect on the array scattering matrix $S$ and on the Total Active Reflection Coefficient (TARC). Also, the envelope correlation between the signals in the antenna ports is almost insensitive to the human presence and remains at very low levels (below 0.1 in the whole ISM 2.4 GHz band).

The array radiation pattern depends on the excitation scheme, therefore all radiation-derived characteristics, namely array radiation efficiency and tissue illumination expressed as Specific Absorption Rate (SAR), are strongly dependent on the array excitation vector. It has been found that, although the user is not in the antenna far-field region, the shape of the SAR distribution in the user torso and head has a qualitative link with the shape of the array radiation pattern. The total power absorbed by the user ranges between 8% and 20% of the array delivered power and depends on the excitation vector. This is in contrast with around 10% absorption, when only one screen integrated antenna element is used. The peak SAR occurs in the user hands and its value strongly depends on the excitation scheme. However, for all the analyzed scenarios the peak SAR (10 g) does not exceed the level of 0.5 W/kg which meets the European safety standards with a large safety margin.

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