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Efficient evaluation of specific absorption rate (SAR) for MIMO terminals

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Abstract: Multi-antenna enabled terminal devices are required to comply with the standards for limiting human exposure to electric fields. However, when compared to traditional single-antenna terminals, a comprehensive evaluation of specific absorption rate (SAR) for multi-antenna terminals is impractical. This is because both the power allocation and phase of the electric fields from different antennas are arbitrary in practical MIMO operation, hence requiring exhaustive evaluation over all possible cases. In this context, this paper first proposes time averaged simultaneous peak SAR (TASPS) as an efficient metric to evaluate exposure when more than one antenna is transmitting simultaneously. Then, it is analytically derived that TASPS will be below a given exposure limit, as long as the stand-alone peak SAR for each antenna is smaller than that limit. Thus, SAR evaluation is greatly simplified since only stand-alone SAR needs to be measured. Several examples of dual-antenna mobile handsets are shown to illustrate and validate the analytical result.

Introduction: The initial focus of multiple-input multiple-output (MIMO) in wireless communications was to improve the downlink (e.g., LTE), meaning that the uplink transmission still only involved one antenna. With the recent launch of LTE-Advanced (LTE-A) [1], multi-antennas can also be used to enhance the uplink. As in the case of single-antenna transmission, devices with multi-antenna transmission are required to comply with the standards for limiting human exposure to electric fields. The exposure of the body to a RF electromagnetic field is usually measured by specific absorption rate (SAR). In a MIMO terminal, stand-alone SAR measures the exposure when only one antenna is transmitting, with the other antennas terminated by their source impedances. In contrast, simultaneous SAR characterises the exposure when more than one antenna is transmitting. In this case, the power level and phase of each transmitting antenna vary rapidly due to MIMO pre-coding and link adaptation. Thus, the superposition of fields from different antennas, i.e., the total electric field, at a given point also varies rapidly. To capture the true simultaneous SAR values, field measurements should be performed quickly over time and at multiple spatial points. Such a comprehensive evaluation is not only technically challenging, but also prohibitively expensive and time-consuming.

So far, there are few literatures on SAR evaluation for multi-antennas [2-4], especially for simultaneous SAR. In particular, field summation schemes based on conventional scalar probes and the corresponding testing methodologies were proposed in [4] for simultaneous peak SAR evaluation. However, the schemes are too conservative for multi-antenna devices.

In this paper, time-averaged simultaneous peak SAR (TASPS) is proposed as an efficient metric to characterise simultaneous SAR, making opportunistic use of the a-priori knowledge that the total field varies rapidly and randomly in time due to channel-dependent MIMO precoding. It is analytically derived that TASPS will always be lower than exposure limit if the stand-alone peak SAR for each antenna is below that limit. Thus, only stand-alone SAR needs to be measured, making the procedure simple since the field from only one transmitting antenna is relatively stable and conventional SAR measurement method and equipment can be used. Three dual-antenna mobile handsets with different antenna types and locations are taken as examples to further establish the practicality of the metric.

TASPS methodology: Since the aim of MIMO technology is to increase the data rate without sacrificing additional frequency spectrum and transmitted power, the total input power (P_{total}) should remain the same regardless of the number of the transmitting antennas.

Considering a MIMO enabled device with n antenna elements, the stand-alone SAR for the pth antenna is expressed as:

$$SAR_p = \frac{\sigma}{\rho}\left|\vec{E}_p\right|^2 , \tag{1}$$

where σ and ρ denote the conductivity and mass density of the tissue, respectively. $\vec{E}_p$ is the root mean square (RMS) electric field in the biological tissue. To comply with a given SAR standard, the peak of stand-alone SAR for each antenna should be smaller than the corresponding limit (L), i.e., $\max(SAR_p) \le L$. For example, for hand-held devices, the SAR limit is L = 2 W/kg when averaged over the 10 g tissue according to the ICNIRP guidelines.

When m antennas ($1< m \le n$) are transmitting simultaneously, the total power is divided among m ports. The power allocated to the pth port is given by:

$$P_p = \alpha_p P_{\text{total}} , \tag{2}$$

where α_p is a real constant with $0 \le \alpha_p \le 1, \sum_{p=1}^{m} \alpha_p = 1$. Since the square of the electric field magnitude is linearly proportional to the input power, i.e., $\left|\vec{E}_p\right|^2 \propto P_p$, the total electric field in phasor form at a given point is given by:

$$\vec{E}_{\text{total}} = \sum_{p=1}^{m} \sqrt{\alpha_p}\, \vec{E}_p e^{j\phi_p} , \tag{3}$$

where ϕ_p is the phase of the electric field generated by the pth antenna, with $\phi_p \in (0°, 360°)$. Thus,

$$\begin{aligned} \left|\vec{E}_{\text{total}}\right|^2 &= \left|\sum_{p=1}^{m} \sqrt{\alpha_p}\, \vec{E}_p \cos\phi_p + j\sum_{p=1}^{m} \sqrt{\alpha_p}\, \vec{E}_p \sin\phi_p\right|^2 \\ &= \sum_{p=1}^{m} \alpha_p \left|\vec{E}_p\right|^2 \\ &\quad + 2\sum_{p\neq q} \sqrt{\alpha_p \alpha_q}\, \vec{E}_p \cdot \vec{E}_q \cos\phi_p \cos\phi_g \; + 2\sum_{p\neq q} \sqrt{\alpha_p \alpha_q}\, \vec{E}_p \cdot \vec{E}_q \sin\phi_p \sin\phi_q \end{aligned} \tag{4}$$

Since power allocation and phase variation are independent from each other, assuming rapid and uniformly distributed phase variation within $(0°, 360°)$, the last two terms in (4) are equal to zero when averaged over time. Then, the time-averaged total electric field is described by:

$$\left|\vec{E}_{\text{total}}\right|^2_{avg} = \sum_{p=1}^{m} \alpha_p \left|\vec{E}_p\right|^2 \quad . \tag{5}$$

According to (1), the averaged simultaneous SAR is:

$$SAR_{avg} = \frac{\sigma}{\rho}\left|\vec{E}_{\text{total}}\right|^2_{avg} = \sum_{p=1}^{m}\alpha_p \frac{\sigma}{\rho}\left|\vec{E}_p\right|^2 = \sum_{p=1}^{m}\alpha_p SAR_p \ , \tag{6}$$

where SAR_p is the stand-alone SAR for each antenna, whose peak value $\max(SAR_p) \le L$. Hence, $TASPS = \max\left(SAR_{avg}\right)$ satisfies:

$$TASPS \le \sum_{p=1}^{m}\alpha_p \max\left(SAR_p\right) \le \sum_{p=1}^{m}\alpha_p L = L \ , \tag{7}$$

where the first equality is only obtained when all peak stand-alone SARs appear at the same location. The second inequality concerns the SAR limit $\max(SAR_p) \le L$. It is concluded from (7) that TASPS always meets the SAR limit as long as each stand-alone SAR meets the limit.

TASPS for dual-antenna mobile handset: As an example application of the metric TASPS, a mobile handset prototype integrated with co-located dual-antennas (see Fig. 1*a*) was simulated in CST Microwave Studio [5]. Identical co-located antennas were chosen because the hotspots of the stand-alone SARs were very close to each other, representing a worse case for simultaneous peak SAR. In this work, a flat phantom having the same properties as that of a human body is used for SAR evaluation, according to the IEC standard for hand-held and body-mounted wireless devices [6]. The flat phantom consists of an inner liquid material of size 225 × 150 × 150 mm^3 and an outer shell with a thickness of 2 mm. The prototype was placed 3 mm above the flat phantom (see Fig. 1*b*).

The 6 dB impedance bandwidth of each co-located antenna was 780-970 MHz in free space. To evaluate SAR, the accepted power at the antennas was set to 24 dBm (0.25W) at 0.859 GHz, the centre frequency of LTE Band 5. For simultaneous SAR, the same accepted power was evenly divided over the two ports, i.e., $\alpha_1 = \alpha_2 = 0.5$. SAR values were calculated according to [6].

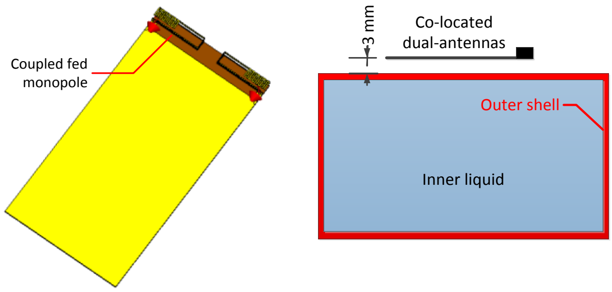

Fig. 1 *System setup for SAR analysis*
a Antenna configuration for handset with dual coupled fed monopole
b Flat phantom and position of MIMO enabled antenna system

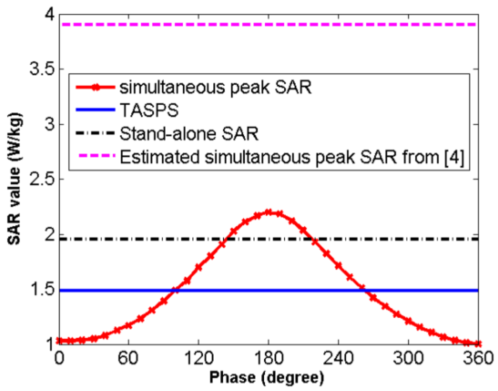

Fig. 2 *Comparison of simultaneous peak SAR, TASPS, stand-alone SAR and SAR estimation from [4] for the mobile handset with dual coupled fed monopole*

Table 1: Comparison of TASPS, stand-alone SAR and SAR estimation from [4] for different dual-antenna mobile handsets

	Maximum of Simultaneous Peak SARs	TASPS	Stand-alone SAR	SAR estimation from [4]
Dual separated monopole [7]	1.4	1.1	1.5	3.1 (120% over estimation)
			1.5	
T-strip and monopole [8]	1.5	1.3	0.5	3.9 (161% over estimation)
			1.6	

To calculate simultaneous SAR, the phase of one antenna was set as the reference (i.e., 0°), whereas the phase of the other antenna varied from 0° to 360° in a step of 10°. The simultaneous peak SARs over different phase shifts between the antennas are shown in Fig. 2, together with the averaged value, the peak stand-alone SAR and the estimated simultaneous peak SAR value using the method in [4]. Stand-alone SAR for only one antenna is shown because the two antennas are identical and symmetrically located on the chassis. It is observed that the simultaneous peak SARs slightly exceed the 2 W/kg limit in the phase range from 160° to 210°. However, assuming uniform random phase variation in time, the probability of the event is relatively low (i.e., 50/360 = 14%). Moreover, due to time-averaging, TASPS is well below the limit, even though the stand-alone peak SAR is just under it. This agrees well with the derivation in (7), showing that it is sufficient to only evaluate stand-alone SAR to ensure exposure compliance. The summation scheme in [4] overestimates the maximum simultaneous peak SAR value by 77%. The overestimation is because the summation scheme is based on the assumption that the stand-alone peak SARs happen at the same location and the electric fields from all different antennas are in phase at that spot.

To further show the practicality of the metric of TASPS, two more dual-antenna handsets [7], [8], in which the antenna types and locations are significantly different from those in Fig. 1, are simulated. The comparisons between different SAR metrics are presented in Table 1. It is found that the maximum value of the simultaneous peak SARs (over different phases) is smaller than the stand-alone peak SAR for each handset, with TASPS having an even lower value. The overestimation of the summation scheme in [4] is more severe for these two handsets than for the co-located antenna handset, since the locations of the stand-alone peak SARs are farther apart.

To ensure the accuracy of our simulation results, we have measured the stand-alone SAR and simultaneous SAR with 0° relative phase in a COMOSAR system. The SAR distributions show good agreements with those in the simulations, but the results are not included in this paper due to space limitation.

Conclusion: SAR evaluation for multi-antenna terminals is practically challenging due to the need to account for power allocation and relative phase among the antennas. However, due to random and fast-varying channel-dependent MIMO precoding, a new metric TASPS can be defined to circumvent simultaneous SAR evaluation. It was shown that TASPS will satisfy the SAR limit by default, as long as the stand-alone SAR of each antenna satisfies the limit. Hence, only stand-alone SAR measurement is needed. The relationship between TASPS, simultaneous peak SAR and stand-alone SAR has been shown for three different dual-antenna mobile handsets.

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