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Dielectric Properties of Human Hand Tissue for Handheld Devices Testing

STANISLAV STEFANOV ZHEKOV, ONDREJ FRANEK, (Member, IEEE), AND GERT FRØLUND PEDERSEN, (Senior Member, IEEE)

Department of Electronic Systems, Technical Faculty of IT and Design, Aalborg University, 9220 Aalborg, Denmark

Corresponding author: Stanislav Stefanov Zhekov (stz@es.aau.dk)

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ABSTRACT The operation of antennas deployed in mobile terminals is affected by the presence of human tissue in their near-field region. Therefore, testing the antenna performance, when the radiator is located in close vicinity to the user, is of paramount importance for any handset. In order to conduct such a study, knowledge about the dielectric properties of relevant human tissues is needed. In this paper, the results for *in vivo* measured complex relative permittivity of the dry and wet human hand palm and fingertip of thumb are presented. For the sake of having a broader set of data, the palms of 22 individuals and thumbs of 16 individuals are tested at multiple points. The measurements are conducted over the frequency band of 5-67 GHz by using an open-ended coaxial probe. The single-pole Cole–Cole model is used for fitting the measured results. Furthermore, the fitting parameters for the multi-pole Debye model are extracted by using the Cole–Cole ones. The effect of the difference in the dielectric properties between dry and wet palm on the performance of a dual-element PIFA antenna array (operating in the band of 5.8-7.7 GHz) is numerically studied. Useful finding for antenna designers is that the S-parameters and radiation efficiency of the antennas are insensitive to the change in the complex permittivity of the hand.

INDEX TERMS Complex relative permittivity, open-ended coaxial probe, palm, thumb, Cole-Cole model, Debye model, user hand effect.

I. INTRODUCTION

The handset antenna operates in a different way in free space and in the vicinity of human tissue. The presence of a lossy human tissue in the near field of the antenna deteriorates its performance [1]–[15]. In order to examine the handset antenna performance under realistic conditions, hand phantoms (apart of head phantom), holding the device under test, have been introduced. Good design of a phantom relies on using appropriate anthropometric and dielectric properties mimicking the human hand. Both of these properties have already been standardized by CTIA [16]. However, the complex relative permittivity has been specified only up to 6 GHz but nowadays more and more wireless systems are expected to operate at higher frequencies. This shows the demand for conducting new studies regarding the dielectric properties of hand tissue at higher frequencies. Apart from that, it is important to study how much the variation in the complex permittivity of the hand between different persons influences the antenna performance. The results from such an investigation will tell the antenna designers whether is needed to test and optimize their radiators for multiple possible values of the complex permittivity of the hand.

Study on the dielectric properties of multiple tissues can be found in [17] while models fitting that data in [18]. However, since the dielectric properties of human palm and thumb are of main interest in this paper the focus is only on them. There are several available publications for *in vivo* measured dielectric properties of palm. The existing hand phantoms have been based on measurements only for palm, i.e. fingers have not been considered. Actually, to the authors' best knowledge, there are no studies about dielectric properties of fingers. However, the fingers are a significant portion of the hand and therefore they should also be studied since they

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have a different structure of the skin (stratum corneum of the palm and fingers contains a different number of layers) [19]. In other words, it is of interest to investigate how large is the difference between palm and fingers in terms of complex permittivity. The standardized dielectric properties for the hand by CTIA [16] have been based on the work in [20], where the palms of 5 individuals have been tested and the mean value for the complex permittivity has been presented. Also, [20] is the only work showing results for wet palm. More results for the mean value of the dielectric properties of palm can be found in: 1) [21] - 7 volunteers have been tested at 4 points; 2) [22] - 12 volunteers have been tested at 1 point; 3) [23] - 10 measurements have been performed; 4) [24] - 42 volunteers have been tested at 1 point; 5) [25], [26] - 1 volunteer has been tested at 1 point. It should be noted that all above mentioned publications have presented data falling within the frequency band of interest in this paper, but the studies in most of them have been conducted over smaller bandwidths.

This paper presents experimental results for the complex relative permittivity of dry/wet palm and fingertip of thumb over the frequency band 5-67 GHz. The novelty of the presented work is: 1) more volunteers are involved in our measurement campaign (in total 22) compared to most of the previous ones discussed in the literature as well as our test is conducted at more points over the surface of the palm in order to see the variance of the complex permittivity between them (the only work where more individuals have been involved is [24] but the tests have been conducted only for one point located on the right palm of the volunteers over the frequency band 20-38 GHz); 2) studying the dielectric properties of fingertip of thumb (not done before) and comparing them with those for palm; 3) studying both palm and thumb dry and wet; 4) investigating the difference in the dielectric properties between the test individuals. Actually, in all above mentioned publications on this topic, only the mean value of the measured dielectric properties for palm has been presented. That is, the data have not been thoroughly analyzed and information about the variation of the complex permittivity among the test points over the surface (the latter is for the publications where more than one point has been studied) and among the test individuals is missing. In general, the investigations conducted by us aim to extend the existing knowledge on the topic of dielectric properties of a human hand. In this paper, a study of the effect of the change in the dielectric properties of the human palm on the performance of an antenna is also conducted. It should be mentioned that a similar investigation based on the total radiated power (TRP) but at different frequencies (900 MHz and 1750 MHz) has been presented in [9]. The mean measured complex permittivity for each of our studies (dry/wet palm and thumb) is fitted by using a single-pole Cole-Cole model. Moreover, for FDTD applications, fitting parameters for multi-pole Debye model are provided and the number of poles needed for accurate representation of the results is studied.

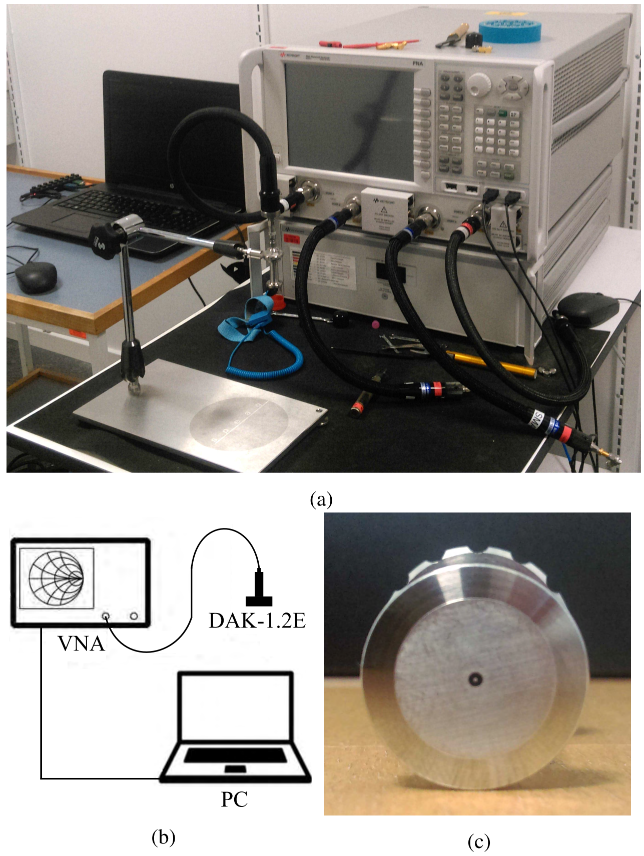

FIGURE 1. (a) Photo of the test system, (b) block diagram of the system, and (c) close view to the probe.

II. TEST SETUP

The setup for measuring the complex relative permittivity ($\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r''$, where ε_r' is the real and ε_r'' is the imaginary part) consists of: 1) vector network analyzer (VNA) - Keysight PNA N5227A; 2) open-ended coaxial probe - DAK-1.2E developed by SPEAG; and 3) PC. The probe covers the frequency band 5-67 GHz. During a test, the probe is in direct contact with the skin surface and the VNA measures S_{ii} (the VNA is operated by the PC). The complex relative permittivity is obtained from the measured reflection coefficient by software developed by SPEAG. Photo of the entire system is shown in Fig. 1(a), block diagram of the system in Fig. 1(b), and close view to the probe in Fig 1(c).

Standard three step calibration procedure was conducted before each test: 1) open; 2) short; and 3) load (deionized water). More specifically, the surface skin temperature of each volunteer was measured right before the test and the temperature of the deionized water (load) was adjusted according to it. Then, the probe was kept in the water so that it was temperature stabilized (before calibration), i.e. to have the same temperature as the load and therefore as the skin. Thus, separate calibration for each volunteer was conducted. The probe was mounted on a stand (see Fig. 1(a)) in order to ensure that the probe (and the cable connected to it) was not moved either during the calibration or during the test of the hand.

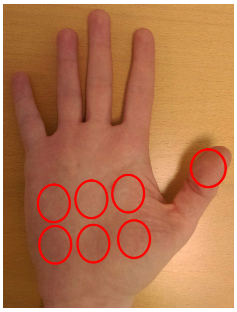

FIGURE 2. Test points over the palm and thumb.

Both palm and thumb were tested dry and wet. Deionized water was used for moistening and the surface water was wiped out before the measurement. In the measurement campaign, 22 individuals (16 men and 6 women) were involved. The volunteers were from three continents and the age difference between the youngest and oldest volunteer was 40 years. The dielectric properties of both right and left palm of each individual were tested. For each palm ε_r^* was measured at 6 points - one per region as shown in Fig. 2. The number of test points was selected as a trade-off between their density and measurement time, i.e. testing at more points would increase the measurement time for each volunteer. Also, the top part of the palm was not studied because the metacarpophalangeal joints are located there. Their presence may complicate the provision that the entire probe is in good contact with the tissue. The complex permittivity of a dry and wet fingertip of thumb of each hand was also measured. However, in this study, only men (in total 16) were involved due to the fact that their thumbs were wide enough to cover entirely the flange of the probe (this was not the case for the women participating in the study). This was also the reason for testing only thumb, i.e. the rest of the fingers (even for men) were not wide enough to cover the flange of the probe which is a requirement for the open-coaxial probe method [27]. The measurements were conducted at 2 points per thumb (only 2 points due to the very limited area over which the measurements can be done) located within the region shown in Fig. 2. The final data were a collection of the measured $\varepsilon_r^*(f)$ − 264 measurements for dry and wet palms [6 points per each right and left dry/wet palm (or in total 12 points for dry/wet palms) of 22 volunteers]; and 64 measurements for dry and wet thumb [2 points per each right and left dry/wet thumb (or in total 4 points for dry/wet thumbs) of 16 volunteers]. It should be mentioned that the frequency step in the measurements was of 400 MHz.

III. MEASUREMENT RESULTS

The mean value and mean value ± standard deviation of the measured ε_r^* for dry and wet palm is shown in Fig. 3. The solid lines in this figure show the mean measured value while the dashed lines are for the mean value ± standard deviation (blue color for dry palm and red color for wet palm). The measurements of wet palm were performed for the sake of investigating the change in ε_r^* due to the higher hydration. There is no standardized procedure for conducting this test, e.g. time for soaking the hand in deionized water, and in the study, it was 30 sec due to time constraints. The effect of the wetness (higher moisture content) on the results can be clearly seen in Fig 3, i.e. higher ε_r' and ε_r'' for wet palm compared to dry one. This behaviour is expected due to the higher dielectric constant and loss factor of water than these for dry human skin. A decrease of both real and imaginary part of ε_r^* with frequency can be observed. The mean real (imaginary) part of the complex relative permittivity measured for dry palm was divided by the mean real (imaginary) part of the complex relative permittivity measured for wet palm and the interval of variation (i.e. maximum and minimum value) of this ratio, found over the studied band, is shown in Table 1 (see "mean dry palm/mean wet palm"). As one can see the differences between dry and wet palm depend on the part of the complex permittivity (i.e. real or imaginary) which is considered as well as they depend on the frequency. In general, both real and imaginary part of the wet palm gets closer to these for dry palm with increasing the frequency. The smallest and largest value of the ratio standard deviation (std) for ε_r' (ε_r'') to mean value for ε_r' (ε_r'') for dry and wet palm (denoted as "std/mean dry palm" and "std/mean wet palm") is presented in Table 1 [the results were obtained dividing the standard deviation of the measured real (imaginary) part of the complex permittivity for dry (wet) palm by the mean measured real (imaginary) part of the complex permittivity for dry (wet) palm]. In general, the ratio standard deviation to mean value for the complex permittivity for both dry and wet palm decreases with increasing the frequency. However, this ratio is smaller for wet palm. The latter means that the variance in the complex permittivity of palm among the test individuals is reduced after moistening. A similar observation has been reported in [20], where it has been stated that moistening greatly reduces the difference in the dielectric properties of skin between the test volunteers. However, in [20] only 5 volunteers have been tested, the time for soaking has not been stated and it has not been explicitly specified how much is this reduction. From the results presented in this paper can be seen that the variation after moistening is smaller but not negligible.

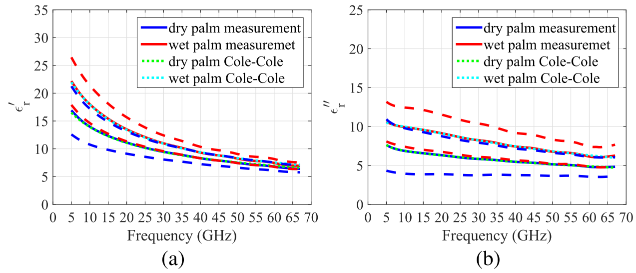

FIGURE 3. Measured and modeled complex relative permittivity for dry and wet palm [blue (red) solid and dashed lines shows the mean measured value and mean measured value ± standard deviation for dry (wet) palm, respectively; green (cyan) dotted line shows the Cole-Cole fit for the mean value for dry (wet) palm]: (a) ε_r', (b) ε_r''.

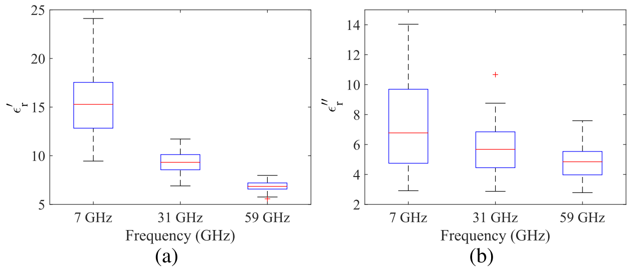

FIGURE 4. Boxplot showing the distribution of the mean complex relative permittivity for dry palm of all test individuals: (a) ε_r', (b) ε_r''.

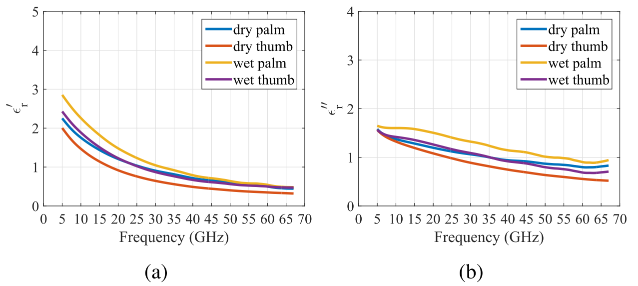

FIGURE 5. Mean value of the difference in the dielectric properties measured at different points on dry/wet thumb and palm of the test individuals: (a) ε_r', (b) ε_r''.

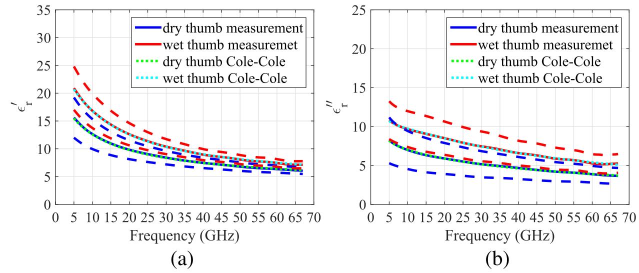

FIGURE 6. Measured and modeled complex relative permittivity for dry and wet thumb [blue (red) solid and dashed lines shows the mean measured value and mean measured value ± standard deviation for dry (wet) thumb, respectively; green (cyan) dotted line shows the Cole-Cole fit for the mean value for dry (wet) thumb]: (a) ε_r', (b) ε_r''.

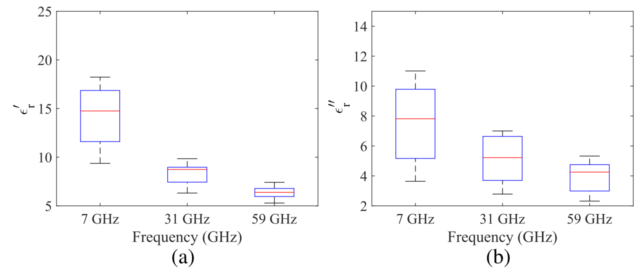

FIGURE 7. Boxplot showing the distribution of the mean complex relative permittivity for dry thumb of all test individuals: (a) ε_r', (b) ε_r''.

Boxplot with the mean values of the complex relative permittivity for the dry palm of all test individuals is presented in Fig 4. Skewness of the data can be seen and also that there is a significant difference between the dielectric properties of the palm of the studied volunteers, especially at low frequencies. Moreover, it can be observed that some of the individuals have quite low/high values for the dielectric constant and loss factor. Fig. 5 shows the mean value of the difference in the dielectric properties measured at different points on the dry/wet palm of the test individuals. As one can see the variation among the points decreases with frequency. Also, for both ε_r' and ε_r'' the difference is higher for wet palm than for dry one. If the relative variance is considered (i.e. the results presented in Fig. 5 are divided by the results for the mean measured complex permittivity presented in Fig. 3) then: 1) for ε_r' for both dry and wet palm the relative variance is similar and it has a value between 0.07 and 0.13 as it decreases with increasing the frequency; and 2) for ε_r'' for dry palm the relative variance is between 0.17 and 0.21, while for wet palm between 0.15 and 0.17 and in both cases the value decreases with increasing the frequency. This means that for ε_r'' the relative variance among the test points is higher for dry palm.

Fig. 6 shows the mean value and mean value ± standard deviation of the measured ε_r' and ε_r'' for a dry and wet fingertip of thumb. The solid lines in this figure show the mean measured value while the dashed lines are for the mean value ± standard deviation (blue color for the dry thumb and red color for the wet thumb). As in the case of palm, the higher water content increases the real and imaginary part of ε_r^* for the thumb. Table 1 presents the minimum and maximum ratio (found over the studied band) between the mean values for real and imaginary parts of ε_r^* for dry and wet thumb as well as the smallest and largest ratio std/mean value for the dielectric properties of dry and wet thumb (the results are calculated in the same fashion as those for palm). Similarly as for palm, the variation decreases when the hydration level is increased. It can be seen that all these variations are close to the ones observed for palm even though fewer measurements for the thumb (fewer volunteers and points over the surface) were conducted. Fig. 7 shows boxplot with the mean values of the dielectric properties for the dry thumb of all test individuals. As for palm, the skewness of the data can be observed and that there is a large difference among the studied volunteers. The difference in the dielectric properties measured at different points on the dry/wet thumb of the test individuals is presented in Fig. 5. Similarly as for the palm, the variation among the points decreases with increasing the frequency and for both ε_r' and ε_r'' the difference is higher for wet thumb than for dry thumb. If the relative variance is considered (i.e. the results presented in Fig. 5 are divided by the results for the mean measured complex permittivity presented in Fig. 6) then: 1) for ε_r' for dry thumb the relative variance is between 0.05 and 0.13, while for wet palm between 0.07 and 0.12 and in both cases the value decreases with increasing the frequency; and 2) for ε_r'' for dry thumb the relative variance is between 0.14 and 0.19, while for wet thumb between 0.13 and 0.15 and in both cases the value decreases with increasing the frequency. That is, the relative variance for dry thumb changes within a wider range.

Fig. 8 shows a comparison between the results for dry/wet thumb and palm. The presented mean complex permittivity and standard deviation for palm are calculated from the

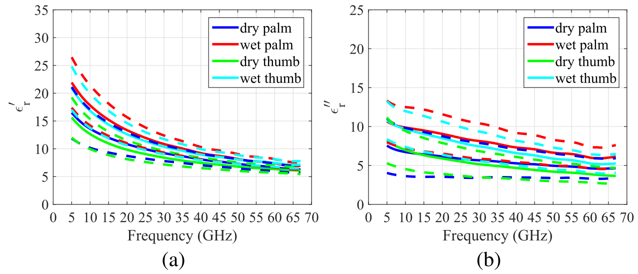

FIGURE 8. Comparison between the measured complex relative permittivity for dry/wet palm and thumb for 16 of the volunteers (with the same color as in the legend for the corresponding scenario: Solid line shows the mean measured value, and dashed lines show the mean measured value ± standard deviation): (a) ε_r', (b) ε_r''.

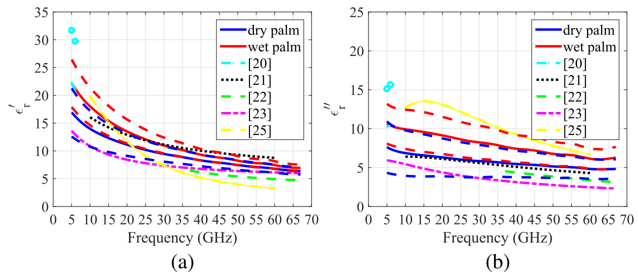

FIGURE 9. Comparison between the results for the complex relative permittivity [(a) ε_r', (b) ε_r''] for palm presented in this paper and the results available in the literature within the frequency band 5-67 GHz (the results presented in this paper are plotted as follows: Red solid line shows the mean measured value for dry palm, red dashed lines show the mean measured value ± standard deviation for dry palm; blue solid line shows the mean measured value for wet palm, blue dashed lines show the mean measured value ± standard deviation for wet palm). In all the works, only dry palms have been studied except in [20] where both dry and wet palm have been tested (cyan dashed line - dry and cyan symbols - wet palm).

data for the same 16 individuals, the thumbs of whom were tested. Differences between the results for thumb and palm can be seen. However, in order to have a better idea about the difference between the datasets, Table 1 (the last two rows) presents the variation, over the studied band, of the ratio between the mean ε_r^* for thumb and palm [calculated from the data presented in Fig. 8, just by dividing the mean real (imaginary) part of the measured complex permittivity for dry (wet) thumb by that for dry (wet) palm]. The difference in ε_r' (up to 9%) is smaller than that in ε_r'' (up to 20%). It should be taken into account that the results for the palm are based on 12 measurements (6 for left and 6 for right palm) per volunteer, while these for the thumb on 4 (2 for left and 2 for right thumb). However, even when the single measurements for each volunteer are compared, a difference in the shape of the curves for ε_r^* for thumb and palm is observed (same can be seen for the mean values in Fig. 8 as it is more strongly pronounced for ε_r''). The explanation for the mismatch between the two datasets is the difference in the structure of the skin of palm and thumb.

A comparison between the results for palm presented in this paper with the ones (also *in vivo* obtained) reported in [20]–[23], [25], falling within 5-67 GHz band, is shown in Fig. 9. In [21]–[23], [25] results only for dry palm have been presented. As one can see in Fig. 9, there are differences

TABLE 1. Variation of ratios for all studied scenarios: Between mean values (mean); and between mean values and standard deviations (std).

Ratio	Variation	
	ε_r'	ε_r''
mean dry palm/mean wet palm	0.76-0.93	0.69-0.79
std/mean dry palm	0.1-0.26	0.26-0.43
std/mean wet palm	0.09-0.19	0.21-0.27
mean dry thumb/mean wet thumb	0.75-0.86	0.69-0.76
std/mean dry thumb	0.1-0.23	0.28-0.36
std/mean wet thumb	0.09-0.19	0.23-0.26
mean dry thumb/mean dry palm	0.91-0.97	0.79-1.09
mean wet thumb/mean wet palm	0.94-1.03	0.86-1.01

between the results available in the literature, which is due to the fact that different individuals have been tested. The results in this paper (in terms of mean value ± standard deviation) encompasses parts of the published ones (for example ε_r' in [23], ε_r'' in [21] and [22], etc.). Some other observations from Fig. 9: 1) ε_r' in [21] above 25 GHz is larger than mean + standard deviation (dry palm) from our study and is much higher than what has been found in the other studies; 2) ε_r' in [25] varies more with the frequency than what has been observed in the other investigations (it should be mentioned that in [25] only one person at one point on the palm has been tested); and 3) ε_r'' in [23], [25] decreases much faster with frequency than what has been seen in the other studies. The standardized values by CTIA for the complex permittivity are the ones for dry palm (5 individuals have been tested) presented in [20]. Fig. 9 shows that the dielectric properties obtained in [20] are much higher than those in [23] (the only other available work in this frequency region). However, both the real and imaginary part of ε_r^* in [20] for dry palm is very close to the mean value + standard deviation shown in this paper also for dry palm. The results for wet palm in [20] (there has not been stated the time for soaking the palm) are higher than the mean value + standard deviation for wet palm presented here. It should be noted that the results for ε_r' and ε_r'' in [20]–[23] are close or fall within the range (between the minimum and maximum value) found in this study. The investigation presented in this paper is based on measurements involving much more volunteers and test points compared to the previously published works. In general, it can be assumed that testing more individuals would give a mean value which is more representative for the dielectric properties of palm. However, as shown in Section V, assigning the complex permittivity for dry or wet palm to a hand phantom has quite a small impact on the antenna performance. In other words, the use of any of the dielectric properties presented in the literature for testing antenna might not lead to significantly different results for the user hand effect on the radiator.

IV. DATA FITTING

A. COLE-COLE MODEL

The mean complex permittivity for dry/wet palm and thumb was fitted by using a single-pole Cole-Cole model. This was

TABLE 2. Fitting parameters for the Cole-Cole model for the mean measured complex permittivity.

Tissue	ε_∞	ε_s	$\sigma_s(S/m)$	$\tau(ps)$	α
Dry palm	1	22.85	0.785	9.775	0.395
Dry thumb	2.769	23.11	0.797	17.253	0.361
Wet palm	2.219	29.03	0.99	11.145	0.288
Wet thumb	3.612	26.99	1.164	12.447	0.256

performed for the needs of easy extraction of wideband data. The single-pole Cole-Cole model is defined as [28]:

$$\varepsilon_c^*(\omega) = \varepsilon_c'(\omega) - j\varepsilon_c''(\omega) = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + (j\omega\tau)^{(1-\alpha)}} + \frac{\sigma_s}{j\omega\varepsilon_0} \quad (1)$$

where the subscript c refers to the Cole-Cole model, ε_c^* is the fitted complex relative permittivity, ε_c' is the real part and ε_c'' is the imaginary part of the permittivity, ω is the angular frequency. ε_s is the static relative permittivity, ε_∞ is the relative permittivity at very high frequency, σ_s is the static conductivity, τ is the relaxation time, and the parameter α is a measure of the broadening of the dispersion [21]. The latter five parameters were extracted from the experimental data and for dry/wet palm and thumb are given in Table 2. The fitting parameters are intended to represent the measurement data only over the studied frequency range.

The fitted curves for the palm are presented in Fig. 3, while these for the thumb in Fig. 6. As one can see the Cole-Cole model well represents the measurements, i.e. the curves from the measurement and the fit overlap. The following error function (named total error in the rest of the paper) was used to quantify and improve the quality of the fit [it was selected since it equalizes the impact of the two dimensions (i.e. the real and imaginary part of the permittivity) on the fit] [29]:

$$e = \frac{\sum_{i=1}^{K}\left(\frac{\varepsilon_r'(\omega_i)-\varepsilon_c'(\omega_i)}{median[\varepsilon_r'(\bar{\omega})]}\right)^2 + \sum_{i=1}^{K}\left(\frac{\varepsilon_r''(\omega_i)-\varepsilon_c''(\omega_i)}{median[\varepsilon_r''(\bar{\omega})]}\right)^2}{K} \quad (2)$$

where K is the number of measurement frequency points ($K = 156$; the frequency step in the measurements was 400 MHz) [it should be kept in mind that this is the number of frequency points (same for palm and thumb) but not test points (different for palm and thumb)], $\bar{\omega}$ is a vector of all measurement frequencies, $\varepsilon_r'(\omega_i)$ and $\varepsilon_r''(\omega_i)$ are the measured values, while $\varepsilon_c'(\omega_i)$ and $\varepsilon_c''(\omega_i)$ are the values from the Cole-Cole fit at frequency ω_i. The lowest total error is $e = 1.1\text{x}10^{-4}$ for the fit for the wet thumb, while the highest one is $e = 1.88\text{x}10^{-4}$ for the fit for the wet palm.

In order to get further insight into the accuracy of the fit, the errors in the real and imaginary part of the complex relative permittivity over the measured frequency band were also studied as:

$$e_r(\omega) = \varepsilon_r'(\omega) - \varepsilon_c'(\omega) \quad (3a)$$

$$e_i(\omega) = \varepsilon_r''(\omega) - \varepsilon_c''(\omega) \quad (3b)$$

The results for the frequency dependent errors in the real $e_r(\omega)$ and imaginary $e_i(\omega)$ part of the relative permittivity for palm and thumb are presented in Fig. 10 and Fig. 11, respectively. The maximum errors for the single-pole Cole-Cole fit for dry/wet palm are 0.4/0.21 units for the real part and 0.11/0.29 units for the imaginary part. The maximum errors for dry/wet thumb are 0.14/0.22 units for the real part and 0.06/0.17 units for the imaginary part. Therefore, the Cole-Cole model fits the data quite well.

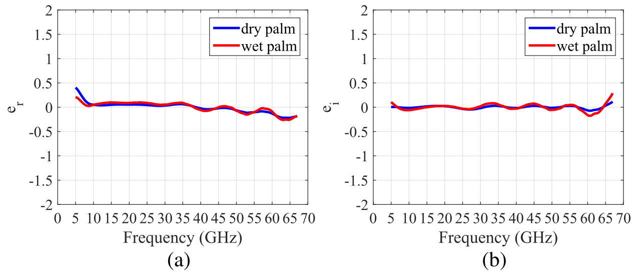

FIGURE 10. Absolute errors in (a) real and (b) imaginary part of the mean complex permittivity for dry and wet palm modelled by using Cole-Cole model.

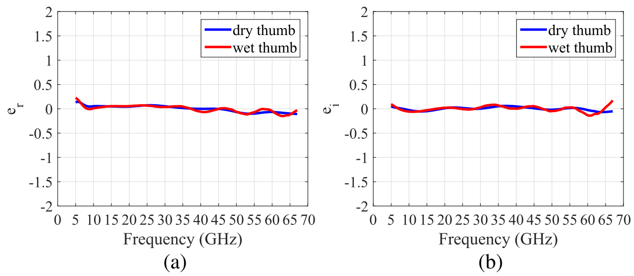

FIGURE 11. Absolute errors in (a) real and (b) imaginary part of the mean complex permittivity for dry and wet thumb modelled by using Cole-Cole model.

B. MULTI-POLE DEBYE MODEL

The implementation of the Cole-Cole model into FDTD codes is more complicated than that of the Debye model [30], [31]. Due to that, it is better to have fitting parameters for the Debye model when comes to performing simulations for studying the interaction antenna - human hand. The used procedure for finding the fitting parameters for the Debye model from these for the Cole-Cole model was as the one explained in [31]. The multi-pole Debye model is defined as [30]:

$$\varepsilon_d^*(\omega) = \varepsilon_d'(\omega) - j\varepsilon_d''(\omega) = \varepsilon_\infty + \sum_{n=1}^{N} \frac{\Delta\varepsilon_{d,n}}{1 + j\omega\tau_{d,n}} + \frac{\sigma_s}{j\omega\varepsilon_0} \quad (4)$$

where d is the subscript refereeing to Debye model and N is the number of used poles. ε_∞ and σ_s are the same as in the Cole-Cole model (see Table 2) while $\Delta\varepsilon_{d,n}$ (magnitude of the dispersion or pole amplitude) and $\tau_{d,n}$ are the parameters which have to be found. The fitting parameters for Debye models with: two-, three-, and four-poles are given in Table 3. The reason to present all of them is to show how the error in the fit changes with the number of employed poles, i.e. the number of poles is increased (standard procedure; see for

TABLE 3. Fitting parameters for the multi-pole Debye models for the mean measured complex permittivity.

Tissue	№ of poles	$\Delta\varepsilon_{d,1}$	$\tau_{d,1}(ns)$	$\Delta\varepsilon_{d,2}$	$\tau_{d,2}(ns)$	$\Delta\varepsilon_{d,3}$	$\tau_{d,3}(ns)$	$\Delta\varepsilon_{d,4}$	$\tau_{d,4}(ns)$
Dry palm	2	1.22	0.392	9.955	11.07				
	3	4.467	0.638	6.094	4.471	7.762	2.104		
	4	3.344	0.392	4.112	2.595	5.681	8.384	6.109	33.428
Dry thumb	2	4.345	1.49	10.172	13.602				
	3	2.703	0.747	4.926	5.15	8.797	2.42		
	4	1.946	0.449	2.868	2.874	5.345	9.452	7.3	3.681
Wet palm	2	6.435	1.65	15.186	11.782				
	3	3.66	0.839	8.47	5.093	11.498	20.207		
	4	2.491	0.508	4.721	2.938	9.083	8.89	8.316	30.795
Wet thumb	2	4.868	1.83	14.2	12.494				
	3	2.588	0.914	7.281	5.45	10.927	20.488		
	4	1.707	0.549	3.674	3.097	8.458	9.309	7.786	30.551

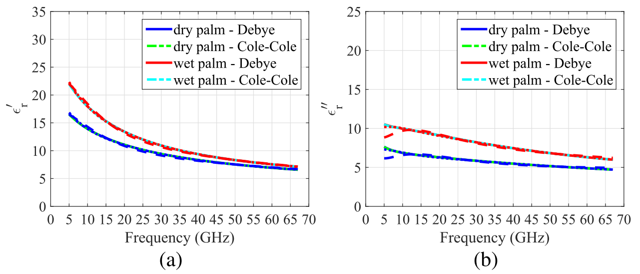

FIGURE 12. Comparison between (a) real and (b) imaginary part of the complex relative permittivity for dry and wet palm modelled by using Cole-Cole model (dash-dotted line) and by using multi-pole Debye models (with the same colour as in the legend for the corresponding scenario: Dashed line shows the two-pole; dotted line shows the three-pole; and solid line shows the four-pole Debye model).

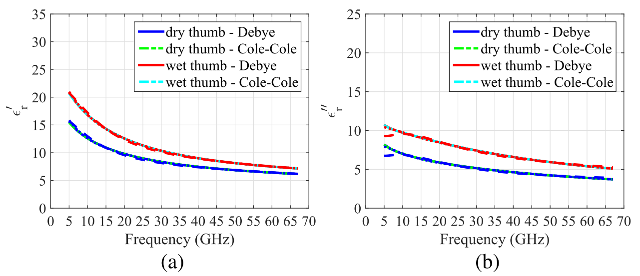

FIGURE 13. Comparison between (a) real and (b) imaginary part of the complex relative permittivity for dry and wet thumb modelled by using Cole-Cole model (dash-dotted line) and by using multi-pole Debye models (with the same colour as in the legend for the corresponding scenario: Dashed line shows the two-pole; dotted line shows the three-pole; and solid line shows the four-pole Debye model).

example [30], [31]) for the sake of improving the fit which can be obtained by using the Debye model instead of the Cole-Cole one. Single-pole Debye model is not given since its inaccuracy is too high.

Fig. 12 and Fig. 13 show the real and imaginary part of the complex relative permittivity obtained from the two-, three- and four-pole Debye models along with these from the Cole-Cole models for palm and thumb, respectively. The real part of the permittivity obtained from the two-pole Debye model shows some variations around the Cole-Cole benchmark data, but in general the agreement is good. However, the difference in the imaginary part at low frequencies is significant. The deviation of the Debye model decreases with increasing the number of used poles from 2 to 4 and gives curves which are essentially indistinguishable from the ones obtained by using the Cole-Cole model.

The total error [defined in a similar as in (2); first ε_c^* is exchanged with ε_d^* and then ε_r^* with ε_c^*] for the Debye model as a function of the number of poles is presented in Table 4 (the fitting parameters for the models with 1 pole and above 4 poles are not presented in the paper). It should be mentioned that all theoretical studies were conducted by using built-in Matlab functions (see [31]). With Matlab, the maximum number of poles for the Debye model which can be found from the Cole-Cole modeled data (for each of the studies) was 13. It can be seen in Table 4 that for all scenarios the absolute value of the total error *e* decreases gradually when increasing the number of used poles up to 8. Above 8 poles, the error does not exhibit a constant trend. Also, the employment of the maximum number of poles does not lead to the minimum total error. The lowest absolute value of the total error is found for: 1) dry palm for 12 poles; 2) dry thumb for 8 poles; 3) wet palm for 12 poles; and 4) wet thumb for 9 poles. This means that if more than 4 poles (the maximum one for which the fitting parameters are given) are employed then the total error can be further reduced. However, as shown in the next paragraph the use of 4 poles already provides quite low relative error and therefore the use of more poles might not be so beneficial.

The absolute errors in the fit for palm and thumb, when using the Debye model, are shown in Fig. 14 and Fig. 15, respectively. Two-pole Debye model gives a too high error for the imaginary part of the relative permittivity at low frequencies, but for the real part is not so significant. The error for the case of four-pole Debye model is very low. According to the results for the maximum relative error (see Table 5) and if generalizing over all scenarios (i.e. real and imaginary part of the relative permittivity for dry/wet palm and thumb) the deviation is above 19% for two-pole and decreases to below 0.8% for four-pole Debye model.

V. USER HAND EFFECT ON ANTENNA PERFORMANCE

So far the measurement results for dielectric properties of dry/wet palm and thumb along with models for fitting the data have been presented. However, it is important to see whether the variation of the dielectric properties among the persons will change the antenna performance dramatically. For the sake of the study, antenna array consisting of two mirrored identical PIFA antennas were designed. The geometry of the

TABLE 4. Total error $e(\mathrm{x}10^{-5})$ for the Debye model as a function of the number of used poles.

Tissue	№ of poles												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Dry palm	1209.5	234.2	45.9	4.66	-0.302	-0.268	-0.071	-0.013	0.008	6.78	-1	0.0006	0.059
Dry thumb	1651.6	316.4	53.6	4.02	-0.741	-0.378	-0.087	-0.008	-0.027	-0.016	-0.019	0.027	58.7
Wet palm	1571.4	172	29.9	2.95	-0.176	-0.162	-0.044	-0.004	0.012	0.032	-0.064	-0.002	-2.95
Wet thumb	1337.7	173.5	29.8	2.82	-0.225	-0.176	-0.046	-0.007	0.003	4.3	0.033	-0.263	-0.01

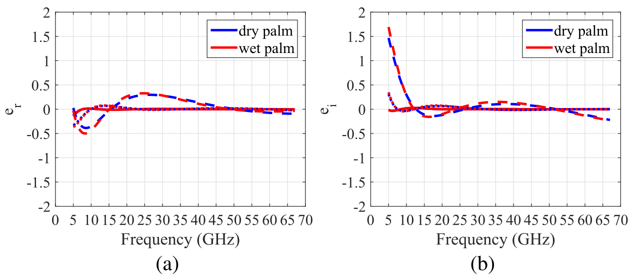

FIGURE 14. Absolute errors in the (a) real and (b) imaginary part of the complex relative permittivity for dry and wet palm modelled by using two-, three-, and four-pole Debye model with respect to the Cole-Cole model (dashed line shows the two-pole; dotted line shows the three-pole; and solid line shows the four-pole Debye model). The error is defined in a similar way as in (3).

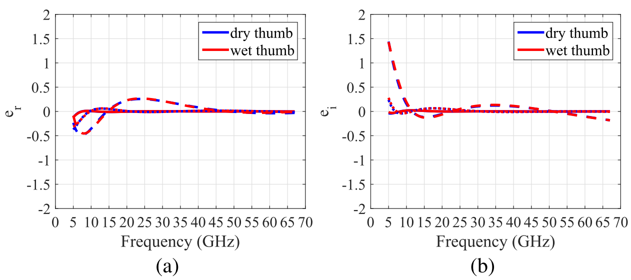

FIGURE 15. Absolute errors in the (a) real and (b) imaginary part of the complex relative permittivity for dry and wet thumb modelled by using two-, three-, and four-pole Debye model with respect to the Cole-Cole model (dashed line shows the two-pole; dotted line shows the three-pole; and solid line shows the four-pole Debye model). The error is defined in a similar way as in (3).

TABLE 5. Maximum absolute value of the relative error (in %) for the mean complex relative permittivity modeled by using multi-pole Debye model: Real part (Re) - $max(|\varepsilon'_c(\omega) - \varepsilon'_d(\omega)|/\varepsilon'_c(\omega))$, imaginary part (Im) - $max(|\varepsilon''_c(\omega) - \varepsilon''_d(\omega)|/\varepsilon''_c(\omega))$.

Tissue	№ of poles					
	2		3		4	
	Re	Im	Re	Im	Re	Im
Dry palm	3.024	19.231	1.993	4.07	0.798	0.447
Dry thumb	3.543	17.591	2.409	2.935	0.794	0.54
Wet palm	2.761	16.075	1.663	3.311	0.664	0.35
Wet thumb	2.516	13.338	1.526	2.62	0.586	0.303

antenna system is shown in Fig. 16(a). The substrate is made of FR4 having a real part of the relative permittivity of 4.3 and loss tangent of 0.025. Also, the substrate has dimensions of 133 x 63 x 0.8 mm^3. The PIFA antennas are located on the left and right corner of the PCB. The ground plane is printed on the same side as the antennas. Also, part of the ground plane (with a length of 3.4 mm) at the edge of the PCB, where the antennas are placed, is removed. As a model of mobile phone housing, a plastic cover (real part of the relative permittivity is of 2.1 and loss tangent is of 0.002) with a thickness of the sides of 1 mm and with total volume of 135 x 65 x 8 mm^3 is used (see Fig. 16(b)). This casing encompasses the entire system and it is in contact with the antennas. All presented studies were conducted by using CST Microwave Studio 2019.

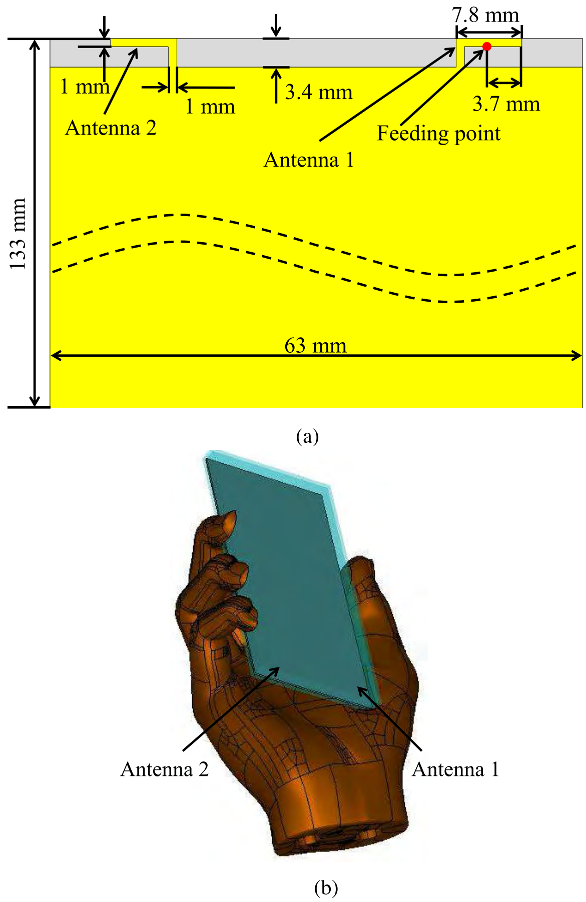

FIGURE 16. (a) Design of the antenna array without the mobile housing and (b) antenna array with the mobile phone housing (semi-transparent) placed in a hand phantom (the antennas are pointing toward the hand).

The simulated magnitude of the S-parameters is shown in Fig. 17. Due to the fact that the antennas are identical and symmetrical S_{11} and S_{22} are the same. The antennas cover the frequency range 5.77 - 7.74 GHz with $|S_{ii}|$ below -6 dB (the range 6.03 GHz - 6.95 GHz is covered with return loss higher than 10 dB). Also, $|S_{21}|$ is lower than -11.5 dB over the covered band. There are two reasons for selecting to design antennas operating at these frequencies: 1) the band 5.9 - 7.1 GHz is a potential candidate for 5G mobile systems [32];

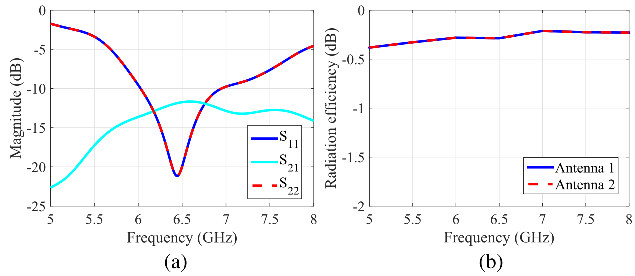

FIGURE 17. **Free space performance of the antenna array: (a) S-parameters and (b) radiation efficiency.**

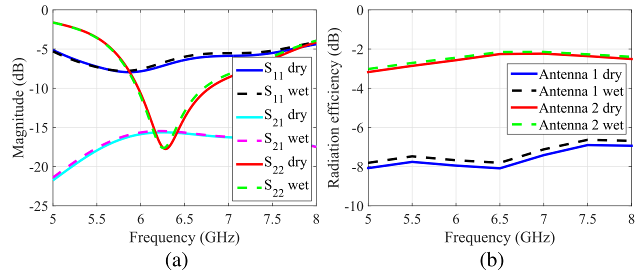

FIGURE 18. **Performance of the antenna array in data mode ["dry" ("wet") denotes the case where the dispersive dielectric properties for dry (wet) palm were assigned to the phantom]: (a) S-parameters and (b) radiation efficiency.**

and 2) within this band the difference between the dielectric properties for dry and wet palm is the highest (below is presented the study on this topic). The radiation efficiency of the antennas is shown in Fig. 17. This parameter varies between -0.3 dB and -0.2 dB over the covered frequency band.

In a typical usage scenario, the user holds the mobile terminal and the vicinity of the hand influences the performance of the handset antenna. More specifically, the input impedance of the antenna changes in the presence of a human tissue. Also, part of the radiated power is absorbed in the tissue which leads to decrease in the radiation efficiency of the antenna. The change in the distribution of the electromagnetic field due to the presence of a human tissue leads to change in the antenna radiation pattern. Many studies have been conducted over the years at low frequencies (sub 6 GHz) for the user hand effect by using phantoms as some of them can be found in [3], [5], [6], [9]–[13]. Also, due to the current research ongoing for 5G systems, user hand effect on the antenna performance at high frequencies (above 6 GHz) has been studied in [14], [15].

In [9] it has been shown that varying the real part of the permittivity and the conductivity of human hand phantom up to 15% does not affect significantly the performance (the TRP value) of the antenna at 900 MHz and 1750 MHz. In a similar way, we conducted study for the effect of the change in the dielectric properties of palm on the antenna performance operating, as stated above, in the frequency band 5.8-7.7 GHz. The antenna system was placed in a hand phantom in data mode as shown in Fig. 16(b). To the phantom were assigned the dielectric properties for dry palm as well as for wet palm taken from the Cole-Cole model (see Table 2), i.e. the modeled mean values were used for the study. We selected to compare the antenna performance between the cases dry and wet palm due to the fact that the difference in their dielectric properties is high. That is, in this way it can be seen whether large difference in the complex permittivity (dry and wet palm have difference in the real part of the permittivity around 30% and in the imaginary part around 40% at 6.5 GHz) of the tissue will result in a significant change in the antenna performance. In order to well investigate the effect, the mock-up was located in the phantom so that the antennas were in the region of the palm (see Fig. 16). More specifically, in this scenario antenna 1 was located quite close to the palm while antenna 2 was away from it. This placement allowed checking how the difference in the dielectric properties of the palm will affect antennas with different distance to this tissue.

Fig. 18 shows the results for the magnitude of the S-parameters in the presence of a human hand ("dry" denotes the case where the dispersive dielectric properties for dry palm were assigned to the phantom, while "wet" denotes the case of complex permittivity for wet palm). As one can see, the matching for antenna 1, which is quite close to the phantom, is much more affected than that for antenna 2 compared to free space (see Fig. 17(a)). In the presence of a human hand shifting of the dip in $|S_{ii}|$ to lower frequencies is observed. However, for each antenna the difference in this shifting between the cases for dry and wet palm is very small. It can be seen that the $|S_{ij}|$ curves in both scenarios are quite similar.

The results for the radiation efficiency of both antennas in the two scenarios are presented in Fig. 18(b). As expected antenna 1 (surrounded by more tissue) shows lower radiation efficiency than antenna 2. The difference between the cases dry and wet palm is insignificant. Based on these results can be concluded that the variation of the complex permittivity among the mobile phone users is expected to lead to small difference in the deterioration of the antenna performance.

VI. CONCLUSION

In this paper, experimental results for the complex permittivity of dry/wet human hand palm and fingertip of thumb have been presented. The measurement campaign has been conducted over the frequency range 5-67 GHz by using an open-ended coaxial probe. The left/right palm of 22 volunteers (each palm has been studied dry and wet at 6 points) and the left/right thumb of 16 individuals (each thumb has been studied dry and wet at 2 points) have been tested.

In all available studies in the literature only the palm has been of interest and the fingers have been neglected. It has been shown that, due to the different structure of the skin of palm and thumb, there is a frequency dependent disagreement between their complex permittivity (up to 20% for the imaginary part). Also, for both palm and thumb has been shown that there is a significant variation among the test persons.

A comparison with data available in the literature has shown a diversity of existing results as the explanation is that different individuals have been involved in the studies. Unfortunately, it has only been presented in all available publications the mean measured complex permittivity and no other information (e.g. standard deviation). In this paper, the difference among the test volunteers and test points has been analyzed more thoroughly.

Through numerical simulations, the effect of the dielectric properties of dry and wet palm on the antenna performance has been studied. The latter has been conducted in order to see whether the variation in the dielectric properties will change significantly the antenna performance. It has been shown that for a concrete antenna array design (two PIFA radiators operating over the band 5.8-7.7 GHz) the change in the S-parameters and radiation efficiencies due to the loading with dry or wet palm (the difference between them is around 30% and 40% for the real and imaginary part of the permittivity, respectively) is insignificant. In general, the effect of the user hand on the antenna performance depends on the design of the radiator. However, based on the results from the presented study as well as the one in [9] the variation in the dielectric properties among the persons might be expected to have a small impact on the antenna performance. Therefore, the factor mainly influencing the antenna performance is the hand grip [9].

The dispersion of the mean complex permittivity has been fitted by the Cole-Cole model. This model well represents the measured results over the studied band. The fitting parameters for multi-pole Debye model have also been presented since this model can be easier incorporated into FDTD codes. It has been found that the employment of 4 poles in the Debye model is enough for having a similar fit as the one from the single-pole Cole-Cole model.

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STANISLAV STEFANOV ZHEKOV received the B.Sc. degree in engineering physics and the M.Sc. degree (Hons.) in wireless communications from Sofia University "St. Kliment Ohridski," Sofia, Bulgaria, in 2013 and 2015, respectively, and the Ph.D. degree from Aalborg University, Aalborg, Denmark, in 2018, where he currently holds a Postdoctoral position at the Department of Electronic Systems. His current research interests include ultrawideband antennas, MIMO antenna design, antenna-user interactions, computational electromagnetics (with a focus on the finite-difference time-domain method), radiowave propagation, and measurement of dielectric properties of biological tissues.

ONDREJ FRANEK (S'02–M'05) was born in 1977. He received the M.Sc. Ing. (Hons.) and Ph.D. degrees in electronics and communication from the Brno University of Technology, Brno, Czech Republic, in 2001 and 2006, respectively. He is currently an Associate Research Professor with the Department of Electronic Systems, Aalborg University, Aalborg, Denmark. His current research interests include biological effects of nonionizing electromagnetic radiation, indoor radiowave propagation, electromagnetic compatibility, and computational electromagnetics with a focus on fast and efficient numerical methods, especially the finite-difference time-domain method. He was a recipient of the Seventh Annual SIEMENS Award for the outstanding scientific publication.

GERT FRØLUND PEDERSEN received the B.Sc.E.E. degree (Hons.) in electrical engineering from the College of Technology, Dublin, Ireland, in 1991, and the M.Sc.E.E. and Ph.D. degrees from Aalborg University, in 1993 and 2003, respectively He was a Consultant for developments of more than 100 antennas for mobile terminals including the first internal antenna for mobile phones, in 1994 with lowest SAR, first internal triple-band antenna, in 1998 with low SAR and high TRP and TIS, and lately various multiantenna systems rated as the most efficient on the market. He has worked most of the time with joint university and industry projects and have received more than U.S. $12 million in direct research funding. Since 1993, he has been with Aalborg University, where he is currently a Full Professor heading the Antenna, Propagation and Networking Lab with 36 researchers. He is also the Head of the Doctoral School on Wireless Communication with some 100 enrolled Ph.D. students. At present, he is the Project Leader of the SAFE Project with a total budget of U.S. $8 million investigating tunable front end, including tunable antennas for the future multiband mobile phones. He has been one of the pioneers in establishing over-the-air (OTA) measurement systems. The measurement technique is now well established for mobile terminals with single antennas. He was chairing the various COST groups (swg2.2 of COST 259, 273, 2100, and ICT1004) with liaison to 3GPP for OTA test of MIMO terminals. He has published more than 175 peer-reviewed papers and holds 28 patents. His current research interests include radio communication for mobile terminals, especially small antennas, diversity systems, propagation, biological effects, and MIMO OTA measurements.