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Actual Diversity Performance of a Multiband Diversity Antenna with Hand and Head Effects

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Abstract **- Using the metric actual diversity gain (ADG), diversity performance is investigated for a compact mobile terminal prototype with two internal, triple frequency band antennas in four different cases of user interaction. ADG is presented as a preferred alternative to apparent diversity gain and effective diversity gain. Absorption due to user proximity causes degradation and imbalance in mean effective gain of the antennas over the frequency bands, contributing to a degradation in diversity performance. However, user-induced changes in the antenna patterns cause a decrease in correlation in the low frequency band, which facilitates increased diversity gain. The study reveals that a significant net diversity gain, i.e., ADG of 5-8 dB compared to a single antenna prototype, can be achieved using multiband antennas in the proximity of a user, even at low frequencies for antennas with high mutual coupling.**

Index Terms **- Handset antennas, correlation, user effects, antenna diversity, actual diversity gain**

I. INTRODUCTION

IMPLEMENTING antenna diversity as an efficient technique to mitigate channel fading and increase transmission quality for handheld devices has been confirmed in earlier work, e.g., [1-3]. However, the trend for mobile terminals is towards smaller and thinner terminal sizes, increasing number of operating frequency bands, and improved transmit and receive performance. Thus, one important challenge lies in implementing multiple multiband antennas that are closely spaced in a compact handset. An additional challenge is the unavoidable interaction with the user.

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The electromagnetic interaction between the multiple antenna device and the user, and its effect on mean effective gain (MEG), correlation, and diversity gain have been a topic of various studies. However, the focus has been on a *single* frequency band using simple and common antenna designs [4-13]. For the case of the planar inverted F-antenna (PIFA) and the whip antenna in the 900 MHz, the diversity handset's MEG decreases in proximity of user's hand, head, and shoulder [4-7]. Depending on the phone/user inclinations and propagation scenario, both increase and decrease of the correlation are observed. However, the diversity gain is consistently high (8-10 dB).

In [8], the presence of a user causes a decrease of MEG for the dual antenna cases (monopole/monopole and PIFA/monopole) at 900 MHz, but there is no change in correlation. In the case of polarization diversity antennas at 900 MHz, the MEG decreases in the proximity of the user and so does the correlation coefficient [9]. Polarization diversity antennas give a degradation of MEG in the presence of a user and a significant increase in envelope correlation at 1800 MHz in [10-11]. The diversity gain is between 8-10 dB. On the other hand, polarization diversity inverted F-antennas at 2 GHz with user effects show MEG degradation and a decrease of the already low correlation [12]. However, diversity gain was not studied. In [13], a large degradation of MEG and no significant change in correlation in the proximity of the user head give a diversity gain of 1 dB at 900 MHz for two co-located half-wavelength dipoles of different polarization angles.

The obvious gain performance degradation seen in the aforementioned studies agrees well with the results obtained for the single frequency band, single antennas in the proximity of a user [14]. However, the behavior of the envelope correlation as well as the relationship between correlation and MEG, and their impact on the diversity performance is not as consistent. Moreover, studying single band antenna designs and placement that gives low mutual coupling offer limited insights for practical receive diversity implementations.

Another important aspect of diversity performance is the metric used. The most common metric is the diversity gain (DG), which is the gain in carrier-to-noise ratio (CNR) obtained at the output of the diversity antenna system, as compared to one of the diversity antennas. Diversity performance is usually calculated in relation to performance of the strongest branch in the diversity antenna system in the case of apparent DG [15], or to a reference antenna with 100% efficiency in free space, in the case of effective diversity gain (EDG) [16]. It can be also calculated in reference to a theoretical upperbound Rayleigh curve as in case of ideal diversity gain IDG [17]. The concept of diversity antenna gain (DAG) [7] takes a similar approach as EDG, in the sense that it facilitates an absolute performance comparison between *different* diversity antenna systems. However, instead of the efficiency used in EDG, the MEG of the strongest branch in the diversity system is multiplied with the apparent DG to obtain DAG. Moreover, the diversity gain is obtained from modulation-dependent bit error rate curves, which gives an indication of the link-level performance. Notwithstanding, apparent DG, EDG, IDG, and DAG are not suitable for antenna designers who would like to know what they can gain from *replacing* a single multiband antenna in the mobile terminal with multiple multiband antennas for diversity combining.

In this paper, diversity performance of a *compact* prototype, with two *internal* antennas with *multiband* coverage and design for practical use, is evaluated for four different user-antenna interaction scenarios. In order to ascertain the potential merits of replacing single antennas with their diversity counterparts in a mobile terminal, we utilize the metric actual diversity gain (ADG) [16], together with the new reference of a single multiband antenna in the same user scenario as the diversity antenna system.

In Section II, we summarize the theory behind the diversity performance metrics used in this paper. In Section III, practically implementable antenna prototypes and their structures are presented. This is followed by a presentation of the experimental approach in Section IV. Section V provides comprehensive simulation and measurement results with comments and discussions. Section VI concludes the paper.

II. THEORY

For the calculation of MEG [18] and envelope cross correlation [19] in this study, statistical power spectrum of the incident fields for both polarizations is assumed to be uniform. Completely uniform environment is characterized by a cross polarization ratio (XPR) of 1 [15].

For selection combining of the received signals from two unequal power branches in a diversity antenna system, the probability that the instantaneous CNR for the combined output is a certain value γ_c is given in [20]. The signal improvement gained from combining signals from two unequal diversity power branches can be extracted by comparing the combined output with the output from one branch at a certain signal probability (e.g., 1% or 50%). The ratio between these two Rayleigh signals is the apparent DG [15-16]

$$\mathrm{DG} = \left.\frac{(\gamma_C/\Gamma_C)}{(\gamma/\Gamma)}\right|_{P(\gamma_C)=1\%\text{ or }50\%}, \tag{1}$$

where γ_c and γ are instantaneous CNR, and Γ_c and Γ are mean CNR for the two Rayleigh signals, respectively. γ is the higher CNR of the two diversity branch signals used as a reference [15]. However, the performance of this branch is affected by the presence of the second branch. Another reference, comprising of an antenna with 100% efficiency in free space was suggested by introducing the metric EDG [16] as

$$\mathrm{EDG} = \frac{(\gamma_C/\Gamma_C)}{(\gamma/\Gamma)_{best\,branch}}\cdot e_{best\ branch}, \tag{2}$$

where the total efficiency $e_{best\ branch}$ takes into account mismatch, dielectric, and conductive losses, as well as mutual coupling losses for the diversity antenna branch with the higher efficiency.

The diversity combined signal can also be related to a realistic single antenna implementation that is to be replaced by the diversity solution used in the *same* user interaction cases. ADG is then formulated as

$$\mathrm{ADG} = \frac{(\gamma_C/\Gamma_C)}{(\gamma/\Gamma)_{single\ antenna\ solution}}. \tag{3}$$

This metric is important for the practical implementation of diversity in a mobile handset since it is able to show the actual effectiveness of replacing a single antenna with multiple antennas. The different diversity performance metrics at different probability levels are illustrated in Fig. 1.

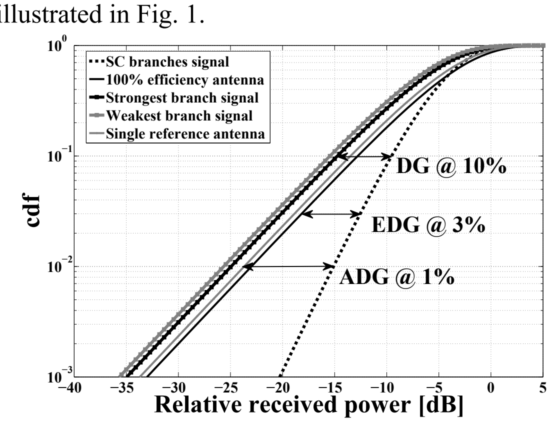


Fig. 1. Definition of diversity performance metrics: apparent diversity gain (DG), effective diversity gain (EDG), and actual diversity gain (ADG).

III. ANTENNA PROTOTYPE DESIGN

a. Diversity antenna prototype

Antenna solutions in this study are practically implementable in a mobile handset. The prototype, with volume of 100x43x9 mm^3, comprises two multiband antennas, each of them not exceeding the volume of 43x20x9 mm^3, and a ground plane with size of 85×40×2 mm^3 (see Fig. 2a, Fig. 3 and Table I). The spacing between the antenna feed points is 85 mm, or 0.24λ, λ being the signal wavelength for the lowest operating band of the prototype, WCDMA850.

The main antenna is a monopole with one of the branches forming a patch with dense meandering end for the WCDMA850 band. The antenna is placed at the bottom end of the prototype. The diversity antenna is a PIFA with a shorted parasitic branch for the UMTS band. Each of the antennas cover the entire receive bands of 869-894 MHz (WCDMA850), 1805-1880 MHz (WCDMA1800) and 2110-2170 MHz (UMTS) at 6 dB impedance bandwidth. The monopole antenna also covers the corresponding transmit frequency bands.

b. Reference antenna prototype

For the purpose of evaluating the merits of replacing a single multiband antenna with two multiband antennas, a reference multiband antenna prototype was used. The reference prototype has the same ground plane size and a similar antenna design as the main antenna in the diversity antenna prototype (see Fig. 2b).

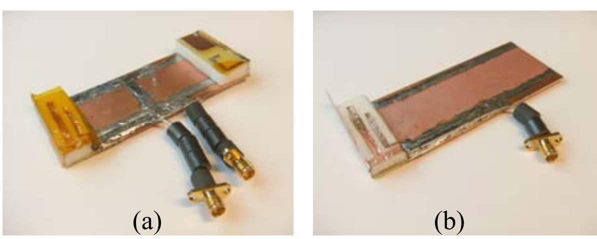


Fig. 2. (a) Diversity prototype, (b) Reference prototype.

IV. SIMULATION AND EXPERIMENTAL SET-UP

The analyses use simulations and measurements as equally favorable tools of actual diversity performance evaluation. The simulations have been performed with the CST Microwave Studio [21] and the measurements in the Satimo Stargate 64 antenna measurement system [22]. The study was performed for four different user interaction scenarios: free space (no user interference), hand position (data mode), head only position (side of head), and hand and head position, as illustrated in Fig. 4. The phantom head and hand simulation files and assemblies, in latest commercially available shapes and dielectric properties, were obtained from IndexSar [23]. Prototype placement in simulations and measurements was with a 0.5 cm air gap from the phantom head/hand, reproducing a common phone chassis thickness.

For each of the four user interference cases and for both antenna prototypes, the far field antenna gain pattern data, efficiencies, and scattering parameters were simulated and measured at nine frequencies, corresponding to the frequencies at the lower edge, midpoint, and higher edge of each of the three receive bands that the prototypes are operating in.

In this paper, the user hand and head effects on the diversity performance are studied for the left head side and left hand. The left side case is preferred due to the placement of the cabling of the prototypes. The cable routing has a significant effect on the mutual coupling and correlation performance [24]. Significant work has been put into choosing a suitable cable configuration. The most suitable one is shown in Fig. 2a. This cable configuration makes measurements for the right side involving head inaccurate due to less practical connection to the measurement system cable.

V. RESULTS AND DISCUSSION

a. Scattering parameters

Measured and simulated reflection coefficients for main and diversity antenna in the diversity antenna prototype, as well as isolation between them, are shown in Fig. 5. Measured and simulated reflection coefficients for the antenna in the reference antenna prototype are shown in Fig. 6. The design of the reference antenna is chosen to resemble the main antenna in the diversity antenna prototype for the purpose of evaluating the performance when one antenna is replaced by two. However, due to presence of the diversity antenna in the diversity antenna prototype, the main antenna and the reference antenna are not designed exactly the same. Minor retuning is required on the reference antenna to retain the 6 dB impedance bandwidth within the operating bands.

b. Mean effective gain, MEG

Fig. 7 shows the radiated performance of the main and diversity antenna for the four different user interaction scenarios. For the antenna in the reference antenna prototype this is shown in Fig. 8. The difference between simulated and measured MEG is 2-3 dB for all the scenarios, an acceptable difference considering complex multiband design and an unavoidable difference in prototype placement between simulation and real measurement set-ups. In free space, the measured MEGs for the main antenna and the diversity antenna are similar at the two lower receive bands. In the highest band, there is a maximum difference of 2 dB. The performance of the main antenna as well as the diversity antenna changes when in proximity of a user,

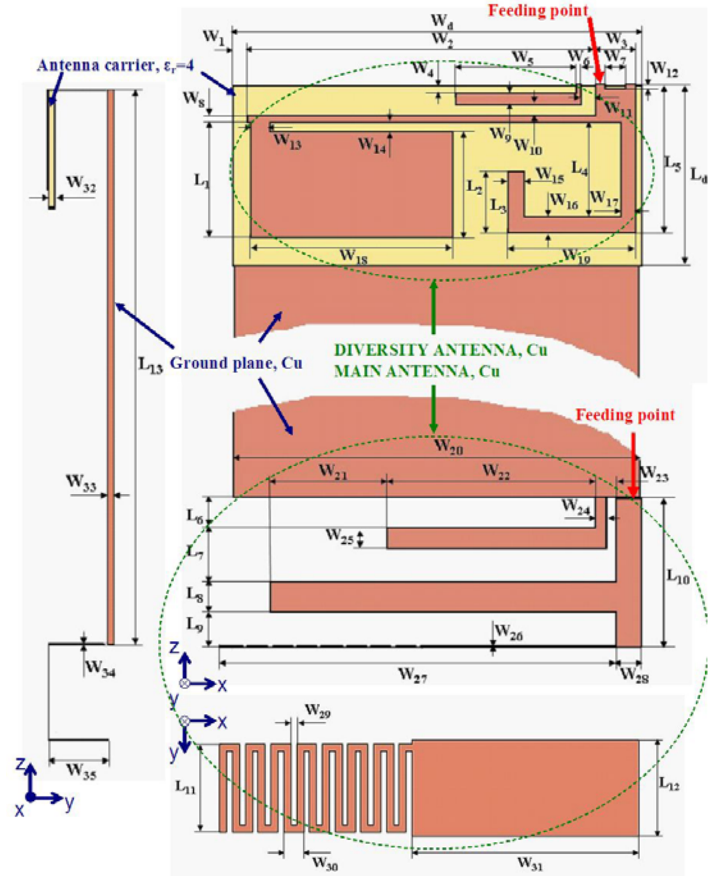


Fig. 3. Geometry of the diversity antenna prototype.

TABLE I
GEOMETRICAL VALUES FOR THE DIVERSITY ANTENNA PROTOTYPE (mm)

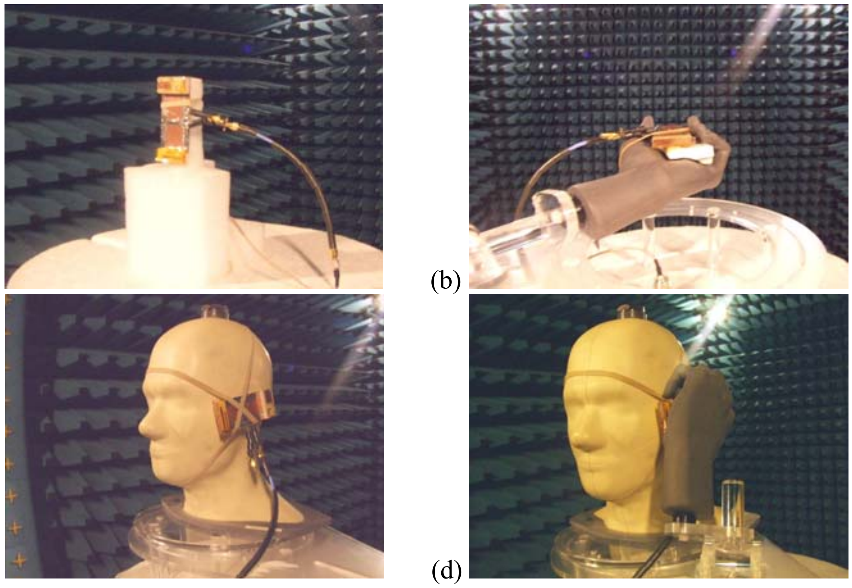
W_d	42	W_{24}	1
L_d	18	W_{25}	2
W_1	2.5	W_{26}	0.1
W_2	34.5	W_{27}	40.5
W_3	4	W_{28}	2.5
W_4	1	W_{29}	0.7
W_5	12.5	W_{30}	2.1
W_6	0.5	W_{31}	22
W_7	2	W_{32}	0.5
W_8	0.5	W_{33}	2
W_9	2	W_{34}	0.1
W_{10}	2	W_{35}	9
W_{11}	1.5	L_1	11.5
W_{12}	0.5	L_2	10.5
W_{13}	2.5	L_3	6
W_{14}	1	L_4	9.5
W_{15}	1.5	L_5	14.5
W_{16}	1.5	L_6	3
W_{17}	1.5	L_7	5
W_{18}	20	L_8	3
W_{19}	12.5	L_9	3.5
W_{20}	40	L_{10}	14.5
W_{21}	11.5	L_{11}	8.5
W_{22}	20.5	L_{12}	9
W_{23}	2	L_{13}	85

causing unequal branch signals. The largest difference in MEG between the two antennas of 4 dB is in the measurement case when the user hand is present (Fig. 7b). The diversity antenna has higher losses in handheld position than the main antenna, mainly due to its placement in the hand; the phantom thumb is in direct contact with the diversity antenna feed.

MEG of the main and the diversity antennas decreases for all user interaction cases in all three bands. The main antenna drops 2-3 dB in performance over the frequencies in the presence of the hand, 3-5 dB in the presence of the head, and 7-8 dB when both head and hand are present. The diversity antenna drops 5-7 dB in the user hand case, 2-4 dB in the head case, and 8-10 dB when both head and hand are present.

Despite the difference in antenna designs and prototype sizes, the results when hand and head are present are consistent with observation in [12] at 2 GHz. For the user head scenario the values are consistent with results in [10] for 1800 MHz.

Measured total loss is presented for the three different user interaction cases relative to the free space performance in Table II. The total loss comprises conductive, dielectric, mismatch, coupling, and absorption losses. Mismatch and coupling losses are calculated from scattering parameters measured for all four user interaction cases and they are presented separately in Table II. The results show that the total loss increases for both main and diversity antennas when a user is present. However, for the main antenna, the mismatch and coupling losses can decrease relative to the free space case. This reveals that the MEG decrease due to the presence of a user is not necessarily caused by a change in the antenna matching and coupling. For example, at 0.88 GHz the mismatch and coupling loss is reduced by 1.6 dB relative to free space case. Despite that, the total loss increases with 1.6 dB relative to free space. The dielectric and conductive losses are approximately the same for all the user interaction scenarios, suggesting that the losses in radiation performance are mainly due to absorption. This gives an absorption loss of 3.2 dB at 0.88 GHz. The diversity antenna has a significant increase in mismatch loss at the lowest frequency band in the head and hand position. However, the MEG decrease is also larger for this case, indicating that the absorption loss is still significant.



(a) (b) (c) (d)

Fig. 4. Four different scenarios for diversity performance evaluation with user interaction, (a) free space (no user interaction), (b) handheld position (data mode), (c) head only position (side of head), and (d) hand and head position.

c. Envelope correlation

The correlation of the signals at the two branches is very high in the lowest band, WCDMA850, and very low in the two higher bands when there is no user interaction, i.e. free space, see Table III. The high correlation is expected at the low frequencies with small antenna separation and radiating chassis [24, 25].

The correlation behavior at different frequency bands and in the presence of a user is attributed to the alteration in the antenna patterns both in magnitude and phase. In order to determine the relative influence of the magnitude and phase alternation of the antenna pattern on the overall correlation, we calculate the correlation from measured magnitude alone patterns (assuming a constant phase over all angles for both antennas), phase alone patterns (assuming magnitude of 1 over all angles for both antennas), and from magnitude and phase (or complex) patterns for the four user cases, see Table IV.

It can be observed in Table IV that the phase only patterns give low correlation values of up to 0.27 for all the bands and user cases, indicating that there are significant variations in the phase patterns between the two antennas. At the same time, the magnitude only pattern in free space is highly correlated at the low frequency. When user hand is introduced, both the overall and magnitude correlation decrease by 0.2. On the other hand, the correlation from the phase increases by 0.1. This suggests that in this case the magnitude perturbation is mainly responsible for causing the decrease in correlation. Figs. 9 and 10 show the radiation characteristics for the two antennas in free space, and hand position, respectively. As can be observed, the user hand alters the radiation characteristics of the two antennas, creating more difference between their magnitude patterns than in free space.

In proximity of only the user head, the magnitude correlation at the low frequencies decreases by 0.3 while the overall correlation decreases by 0.5. And since the phase correlation is unchanged at 0.01, the overall correlation is dominated by the phase behavior. When the user head and hand are introduced, both the magnitude correlation and the overall correlation decrease by 0.1, whereas the phase only correlation increases by 0.3. This suggests that the magnitude alteration is dominant in the correlation performance. In [5], variation in the phase difference between the antennas is identified as the main cause of the change in correlation. This is because in these cases the variations in the magnitude patterns for different user cases are observed to be very small and thus the magnitude correlation is almost unchanged.

The low value of correlation at the higher frequencies is not significantly affected by the user interaction in this study. This is because the spatial separation of the two antennas is sufficiently large at the higher frequencies (>0.5λ) and good decorrelation is more easily obtained. It is noted that a magnitude correlation of roughly 0.6 appears to be a sufficient condition for zero overall correlation, providing that the phase correlation is very low. The correlation behavior described in this subsection is also substantiated by the correlation results from simulated antenna patterns, i.e., the trend is not due to the routing of the cables in the measurement set-up. Acceptable agreement is achieved between the simulated and measured values of envelope correlation in Table III.

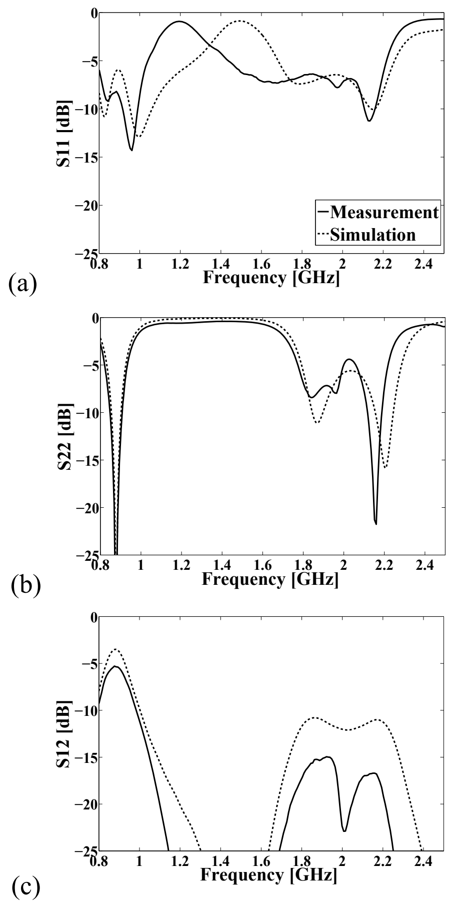


Fig. 5. Simulated and measured a) main antenna and b) diversity antenna reflection coefficient, and c) antenna isolation.

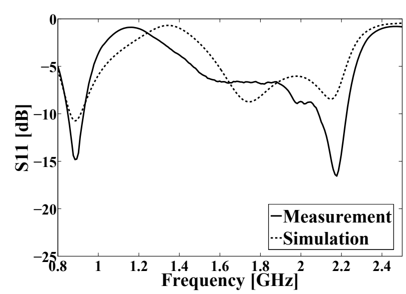


Fig. 6. Simulated and measured reflection coefficients of the antenna in the reference antenna prototype.

d. Diversity performance

A summary of diversity performance for the diversity antenna prototype for all the user interaction cases is presented in Fig. 11. Apparent DG is between 8-10 dB regardless of the user interaction for the diversity antenna prototype. If instead the EDG is considered, the results are more scattered. In the handheld position, the EDG is very low, especially in the lowest frequency band. When the user hand and head are present, there is nothing to gain in the higher bands by using receive diversity measured as EDG. At low frequencies, the EDG is actually negative in value, due to the 100% efficiency reference antenna performing better than the diversity prototype with user interaction. Thus, the DG appears to be an optimistic measure of diversity performance, as it promises good performance regardless of the antennas used [4-7, 10-11] or the user interaction scenario. On the other hand, EDG tends to be overly conservative, as it compares the diversity antenna system with a non-real antenna with no user interaction.

The ADG aims to strike a balance between the two metrics of DG and EDG. The ADG reveals exactly how much can be gained in diversity performance if multiple antennas are used instead of a single one. Therefore, the MEG performance of the reference single antenna in all four user interaction cases plays an important role in the ADG performance. As can be seen in Fig.11, replacing a single antenna with a main antenna plus diversity antenna will give an ADG of about 5-6 dB in free space and handheld position at the lowest band. For the cases of head only position, and head and hand position, the ADG is even higher, at 8-10 dB. In the two higher bands, the ADG is 8-10 dB regardless of the user scenario.

VI. CONCLUSIONS

MEG for both main and diversity antenna in a diversity antenna prototype decreases in the presence of a user, in agreement with previous studies. The user interaction and the antenna type affect the amount of the decrease. The decrease of MEG is mainly due to absorption for the four studied user cases.

The envelope correlation at the lowest frequency band is higher than at the two higher frequency bands with no user present, due to closely spaced antennas (in terms of wavelength). There is a decrease in correlation for all user interaction cases as compared to free space case at the lowest frequency band, despite the presence of high mutual coupling between the two antennas. When the user is present, the interaction between the antennas, chassis, and user alters both the magnitude and phase of the radiation patterns, resulting in a reduced antenna branch correlation. Depending on the user case, the magnitude or the phase plays the dominant role to decrease the correlation. The envelope correlation in the two higher frequency bands is very low, and did not change significantly for any of the user interaction cases. The low correlation at these frequencies is due to high variation in the phase difference between the patterns.

Low correlation facilitates ADG of 8-12 dB, despite low MEGs and unequal antenna branch signals. ADG serves the purpose of determining the actual merits of replacing a compact single reference antenna with its diversity counterpart. Hence, ADG depends on the performance of the reference single antenna. The ADG metric was compared to the DG and EDG, and we conclude ADG strikes a good balance between DG and EDG, which give two extremes in diversity performance.

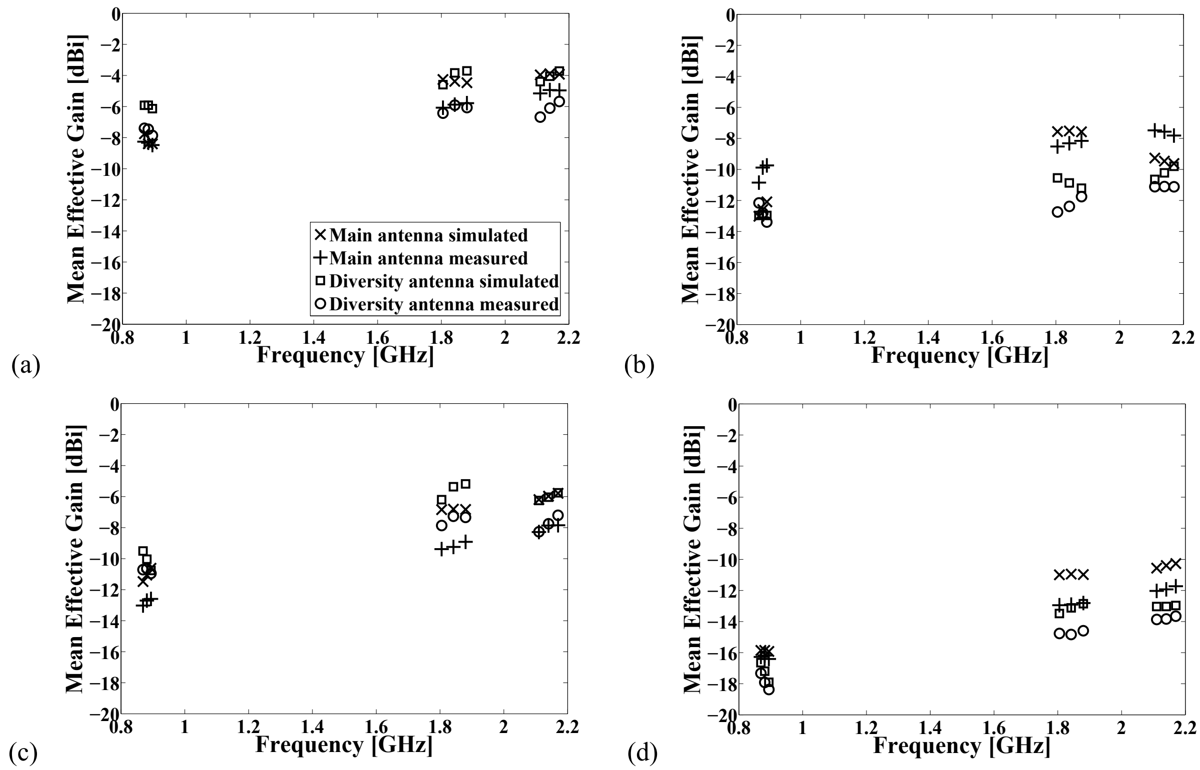


Fig. 7. Mean effective gain for simulated and measured main and diversity antenna for the diversity prototype and user interaction scenarios: (a) free space, (b) handheld position, (c) head only position, and (d) hand and head position.

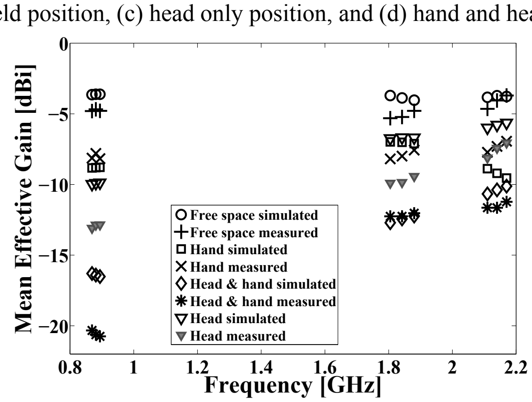


Fig. 8. Mean effective gain for simulated and measured antenna in the reference prototype for all four user interaction scenarios.

TABLE II.
TOTAL RADIATION LOSSES, AND MISMATCH AND COUPLING LOSSES FOR HAND, HEAD, AND HAND & HEAD MEASUREMENT CASES RELATIVE TO THE FREE SPACE MEASUREMENT CASE

		Hand		Head		Hand & Head	
	Frequency [GHz]	ΔTotal loss[1] [dB]	ΔMismatch & coupling loss[2] [dB]	ΔTotal loss [dB]	ΔMismatch & coupling loss [dB]	ΔTotal loss [dB]	ΔMismatch & coupling loss [dB]
MAIN ANTENNA	0.88	-1.60	1.60	-4.40	1.20	-7.90	2.20
	1.84	-2.40	0.90	-3.40	0.00	-7.00	1.10
	2.14	-2.60	-0.10	-2.90	0.00	-7.00	0.20
DIVERSITY ANTENNA	0.88	-5.30	-0.70	-3.20	0.20	-10.50	-2.10
	1.84	-6.50	0.40	-1.40	0.40	-8.90	0.70
	2.14	-5.00	0.00	-1.70	-1.20	-7.70	-0.30

[1] Δ Total loss = $\Delta MEG = MEG_{USER\ CASE}$ (dB)-$MEG_{FREE\ SPACE}$ (dB)

[2] Δ Mismatch & coupling loss =$(1-|S_{11}|^2-|S_{21}|^2)_{USER\ CASE}$ (dB)- $(1-|S_{11}|^2-|S_{21}|^2)_{FREE\ SPACE}$ (dB)

TABLE III.
MEASURED (MEAS) AND SIMULATED (SIM) ENVELOPE CORRELATION FOR FOUR DIFFERENT USER INTERACTION CASES: FREE SPACE, HANDHELD POSITION, HEAD ONLY POSITION, AND HAND AND HEAD POSITION.

	Free space		Hand		Head		Hand & Head	
Frequency [GHz]	Corr. MEAS	Corr. SIM	Corr. MEAS	Corr. SIM	Corr. MEAS	Corr. SIM	Corr. MEAS	Corr. SIM
0.87	0.57	0.65	0.31	0.03	0.01	0.04	0.45	0.16
0.88	0.51	0.56	0.34	0.06	0.00	0.09	0.39	0.16
0.89	0.47	0.52	0.33	0.12	0.03	0.15	0.33	0.14
1.81	0.00	0.00	0.01	0.06	0.01	0.00	0.02	0.15
1.84	0.00	0.01	0.01	0.08	0.01	0.01	0.01	0.13
1.88	0.00	0.02	0.01	0.09	0.01	0.02	0.01	0.12
2.11	0.00	0.00	0.00	0.05	0.03	0.02	0.04	0.05
2.14	0.00	0.00	0.00	0.05	0.03	0.02	0.05	0.05
2.17	0.01	0.01	0.01	0.05	0.05	0.02	0.07	0.04

TABLE IV.
ENVELOPE CORRELATION CALCULATED FROM MEASURED RADIATION MAGNITUDE AND PHASE, TOGETHER AND SEPERATELY FOR THE FOUR DIFFERENT USER INTERACTION CASES AND MID FREQUENCIES FOR THREE DIFFERENT OPERATING BANDS

Correlation		Frequency [GHz]		
		0.88	1.84	2.14
Free Space	Magnitude	0.89	0.68	0.63
	Phase	0.01	0.00	0.01
	Overall	0.51	0.00	0.00
Hand	Magnitude	0.70	0.64	0.62
	Phase	0.10	0.01	0.01
	Overall	0.34	0.01	0.00
Head	Magnitude	0.58	0.58	0.53
	Phase	0.01	0.00	0.02
	Overall	0.00	0.01	0.03
Hand & Head	Magnitude	0.77	0.63	0.64
	Phase	0.27	0.01	0.05
	Overall	0.39	0.01	0.05

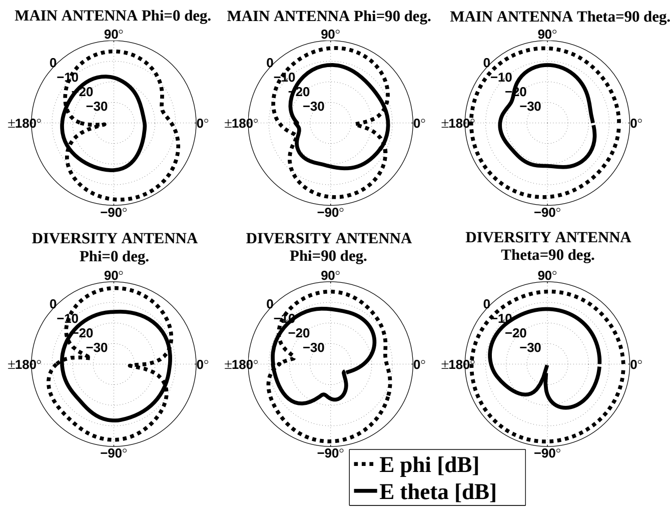


Fig. 9. Magnitude radiation patterns of the main and diversity antenna at 0.88 GHz and in free space

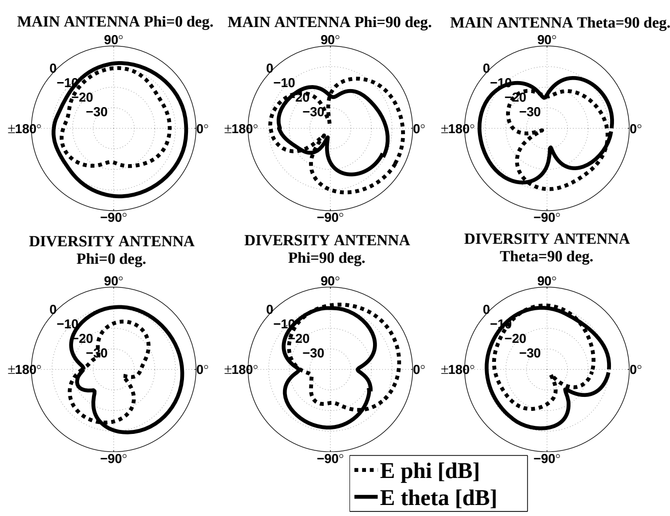


Fig. 10. Magnitude radiation patterns of the main and diversity antenna at 0.88 GHz and in a user's hand

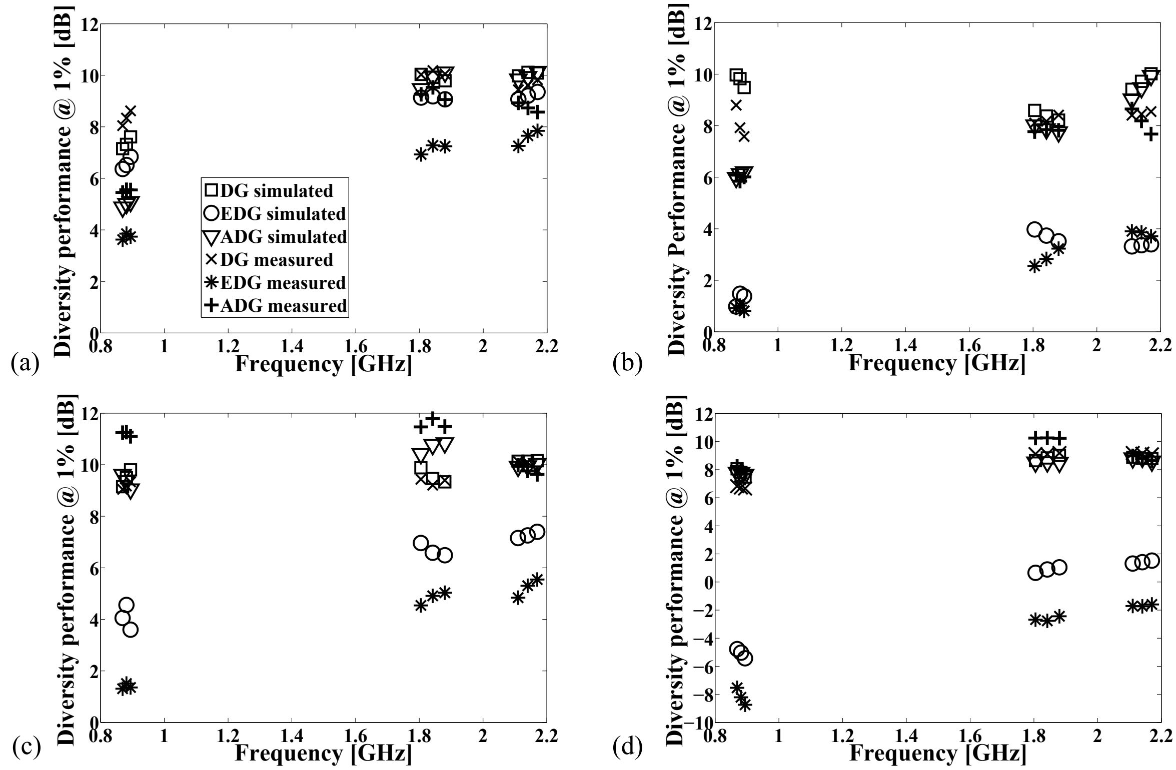


Fig. 11. Simulated and measured diversity performance at the 1 % probability level for the four user interaction scenarios: (a) freespace, (b) handheld position, (c) head only position, and (d) hand and head position.

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