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Boyan Yanakiev
Lindholm Brygge 35
9400 Nørresundby
Denmark
Phone: +45 60699017
Fax: +45 98151564
Email: boyan.yanakiev@molex.com

Correlation Measurements on Small Mobile Devices

Boyan Yanakiev*†, Jesper Ø. Nielsen†, Morten Christensen*, Gert F. Pedersen†
*Molex Antenna Business Unit, Lindholm Brygge 35, 9400, Nørresundby, Denmark
Email: {boyan.yanakiev; morten.christensen}@molex.com
†Faculty of Engineering and Science, Dept. of Electronic Systems, (APNet), Aalborg University
Niels Jernes Vej 12, 9220, Aalborg, Denmark
Email: {by; jni; gfp}@es.aau.dk

***Abstract*—Here, analysis of the antenna correlation at the design stage is done, with focus on measurement techniques. Various theoretical definitions of correlations are used with the corresponding measured data required. The problems related to the coaxial measurement cables, when calculating correlation through the radiation patterns, are analyzed and an optical solution proposed. It is shown that using optical cable replacement, repeatable and accurate measurements of the envelope correlation coefficient can be made.**

***Index Terms*—antenna, correlation, MIMO systems, electrically small antennas, optical fiber, measurements, optical fiber measurement applications, handset antennas**

I. Introduction

Despite the commercial launch of the new 4G mobile standards in multiple countries, many aspects of the performance evaluation and comparison of small mobile devices are still unclear. For example, typically manufacturers would be asked to design devices with antenna envelope correlation of either $\rho_e < 0.7$ or $\rho_e < 0.5$ depending on the source - [1]–[3] and [4], [5], respectively. Little or nothing is said however on how those are to be measured. The current industry standard for certification measurements [6] does not include any Multiple Input - Multiple Output (MIMO) parameters.

This paper looks into the potential pitfalls when measuring correlation using different definitions and assumptions from academic literature. A repeatable and reliable method is sought, usable in industry and with good agreement with simulation predictions.

II. Theoretical Background

A. Correlation Formulations

The definition of antenna correlation was first introduced in [2], computed from the radiation pattern of the antennas and the distribution function of the incoming channel power, Eq. (1).

$$\rho_e \approx \frac{|R_{xy}|^2}{\sigma_x^2 \sigma_y^2} \tag{1}$$

where R_{xy} is the cross covariance, and σ_x and σ_y are the standard deviations of the received signals. R_{xy} can be written in a convenient way as in [7]:

$$\begin{aligned} R_{xy} = \oint \Big[\; XPR \; \vec{E}_{\theta X}(\Omega)\vec{E}^*_{\theta Y}(\Omega)p_\theta(\Omega) \; + \\ \vec{E}_{\phi X}(\Omega)\vec{E}^*_{\phi Y}(\Omega)p_\phi(\Omega)\Big] \, d\Omega \end{aligned} \tag{2}$$

where $XPR = \frac{\theta \; PolarizedPower \; (P_\theta)}{\phi \; Polarized \; Power \; (P_\phi)}$ is the cross polarization ratio of the environment as defined in [8]. The variances can be written as:

$$\sigma_i^2 = \oint \left[XPR \; G_{\theta i}(\Omega)p_\theta(\Omega) + G_{\phi i}(\Omega)p_\phi(\Omega)\right] d\Omega \tag{3}$$

Above, i represents both X and Y antennas, and if ψ stands for both θ and ϕ vector components, then $\vec{E}_{\psi i}(\Omega)$, $G_{\psi i}(\Omega)$ and $p_\psi(\Omega)$ are respectively, the electric fields and gain patterns in the far field of the i-th antenna, and the power distribution function in the environment. Ω indicates variation over both θ and ϕ spherical angles, and * is the complex conjugate.

Assuming isotropic incoming power with $XPR = 1$ and $p_\psi(\Omega) = 1/(4\pi) = const.$, Eq. (2) and Eq. (3) can be simplified and Eq. (1) becomes:

$$\rho_e \approx \frac{\left|\oint \left[\vec{E}_{\theta X}(\Omega)\vec{E}^*_{\theta Y}(\Omega) + \vec{E}_{\phi X}(\Omega)\vec{E}^*_{\phi Y}(\Omega)\right] d\Omega\right|^2}{\oint \left(G_{\theta X}(\Omega) + G_{\phi X}(\Omega)\right) d\Omega \oint \left(G_{\theta Y}(\Omega) + G_{\phi Y}(\Omega)\right) d\Omega} \tag{4}$$

An additional assumption of lossless antennas can be useful to derive the correlation formulation from scattering parameters given in [9] as:

$$\rho_e = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{(1 - (|S_{11}|^2 + |S_{21}|^2))(1 - (|S_{22}|^2 + |S_{12}|^2))} \tag{5}$$

where S_{ij} are the scattering parameters of a two port network. Below, Eq. (4) and Eq. (5) will be used for correlation computation implying the isotropic incoming power distribution function in both cases and lossless antennas in the latter. [10] gives a comparison of the most recent channel models considered, representative for MIMO propagation and all of them are not isotropic. This commonly used assumption however is very convenient to work with and makes the comparison between Eq. (4) and Eq. (5) somewhat more fair. In addition it leaves only the radiation pattern as a variable,

TABLE I
HANDSET OVERVIEW

Handset	Ant. No.	Ant. Type	Antenna Location	Low Band	High Band
H1 PDA	1	mono	Top.-Center	✓	✓
	2	mono	Bot- Center	✓	✓
H2 PDA	1	mono	Top.-Right	✓	✓
	2	mono	Bot- Right	✓	✓
H5 PDA	1	mono	Top-Right	✓	✓
	2	mono	Top-Left	✓	✓
H6 PDA	1	mono	Top-Right	✓	✓
	2	mono	Top-Center	✓	✓

TABLE II
TYPICAL PARAMETERS FROM LAB MEASUREMENTS.

Handset ID	Parameter	Band [MHz]			
		796		2300	
		Ant. No.		Ant. No.	
		1	2	1	2
H1	Eff. [dB]	-3.91	-4.81	-2.56	-3.70
	S_{21} [dB]	-10		-18	
	BPR$_{Iso}$ [dB]	-0.9		-1.14	
H2	Eff. [dB]	-4.19	-4.80	-1.60	-1.53
	S_{21} [dB]	-10.5		-16.5	
	BPR$_{Iso}$ [dB]	-0.9		-18	
H5	Eff. [dB]	-3.31	-3.22	-1.69	-1.89
	S_{21} [dB]	-6.5		-17.5	
	BPR$_{Iso}$ [dB]	0.09		0.2	
H6	Eff. [dB]	-4.53	-2.57	-2.94	-1.83
	S_{21} [dB]	-6.0		-11	
	BPR$_{Iso}$ [dB]	1.96		1.11	

which means that accurate pattern measurements should be sufficient for accurate correlation computation.

B. Optical Measurements

Accurate and repeatable measurements of a small antenna radiation patterns are problematic when using a conductive coaxial cable. The current running on the handset body, [11], interacts with the measurement cables and corrupts the measured result. [12] proposes ferrite beads to be placed on the feeding cables, acting as absorbers for the current on the cables. [13] shows that the position, from which the cable is lead out can be optimized for lower influence. [14], [15] and [16] explore the use of balun chokes to suppress the effect. In all of the above cases however, the cable remains physically present during the measurement and some errors are unavoidable.

To completely remove the cable effect a non-galvanic connection to the antenna is required. One popular solution is the use of optical fibers for delivering the analog RF signal, [17]–[20]. Some simulation results demonstrating the problem when measuring with cables, are shown in [20]. This paper confirms these with measurements and elaborates on the measurement accuracy of the optical system substitute.

The optical set-up used is similar to what other authors have reported in [21]–[23].

III. MEASUREMENTS SET-UP

The handsets used in this paper were prepared for a large scale measurement campaign in May 2011 in Aalborg, Denmark. Four of them having the problematic low band, will be analyzed here. Table I and Table II list some details and lab measurements data. All handsets have Personal Digital Assistant (PDA) form factor, with electrical dimensions of 59×111 mm, typical for modern smart phones.

All patterns used with Eq. (4) are measured in an anechoic chamber sweeping between $\theta = 0-165$ deg. and $\phi = 0-360$ deg. The missing 15 degrees on the bottom of the sphere are not included in the computation. In the case of cabled measurements, a thin, rigid coaxial cable was used with multiple ferrite beads on it. The location, where the cable leaves the handset was chosen for minimum disturbance. The position of the cable after leaving the handset was not controlled.

When measuring the scattering parameters, the handset was placed on a large Styrofoam block with the same cables with ferrite beads used.

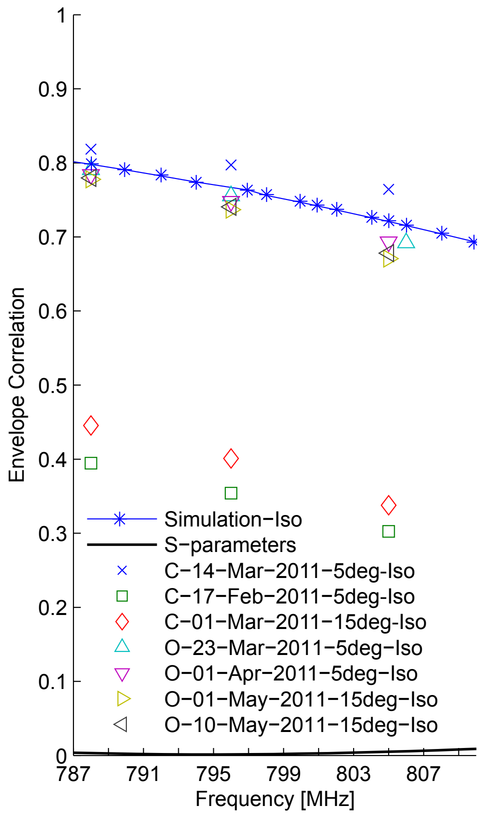

Fig. 1. Correlation in different cases for H1

IV. MEASUREMENT RESULTS

The measurement results for H1 are summarized in Fig. 1. In the figure patterns measured with cables have the prefix C and the ones measured with an optical cable replacement system, the prefix O. The 5 and 15 degrees in the legend refer to both θ and ϕ angular stepping angles for

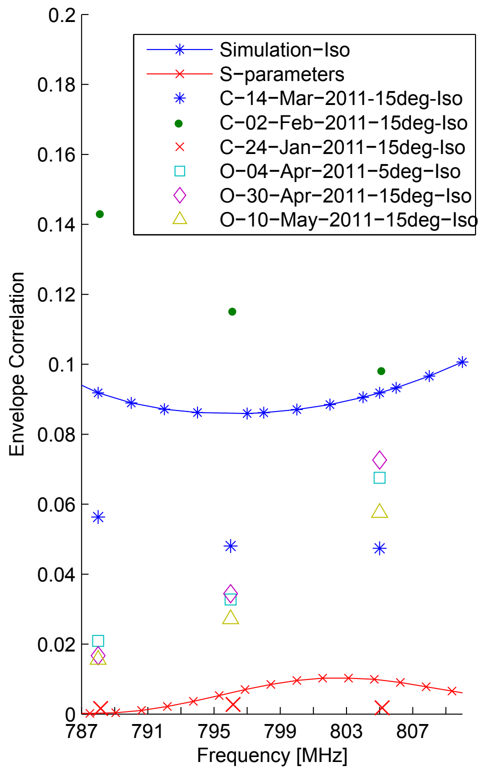

Fig. 2. Correlation in different cases for H2

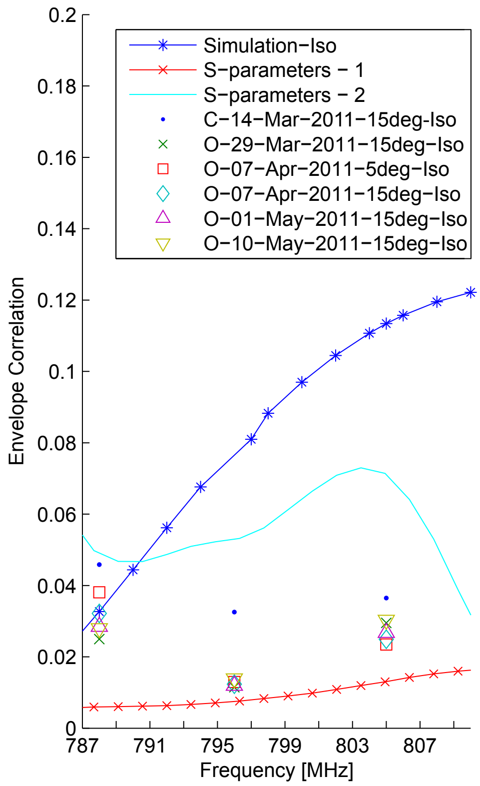

Fig. 3. Correlation in different cases for H5

the particular measurement. The correlation computed from the simulated radiation pattern fits very well with all optical measurements and only one of the cabled ones. This is a result of the uncertainty introduced by the measurement cables. The variation of the cabled measurements is huge and fits well with predicted variations in [20]. The optical system however gives accurate, stable values around the expected one. Moreover, the difference in radiation pattern sampling is not of big importance, indicating that no extra time would be needed compared to an efficiency measurement for example. All measurements are given with the date when they were performed to demonstrate the long term stability of the results. Finally it must be noted that the correlation computed from the scattering parameters gives completely inadequate values. This is most probably due to the disturbance of the Vector Network Analyzer (VNA) measurement cables, and the violation of the lossless assumption, under which Eq. (5) is derived. However, the efficiency values listed in Table II are typical for such handsets, making Eq. (5) useful only for quick estimates in simulation, where most materials are modeled lossless.

Details for handsets H2, H5 and H6 are given in Fig. 2, Fig. 3 and Fig. 4, respectively. In all cases the cabled measurements are with very poor repeatability, while the optical ones are very consistent. When looking into a low correlated handset such as H2 or H5 it is expected that the cable would have somewhat smaller effect. Also the accuracy of the optical system drops because of limited isolation between the ports or additional noise introduced by the lasers.

It is interesting also to look at the accuracy of measuring a single antenna pattern in the case of cables vs. optics. Computing correlation of the patterns from consecutive measurements on the same antenna can be used as an estimate of how repeatable the measurement is. In the case of cables for H1, the computed correlation between the three measurements is in the range of 0.76-0.83. The addition of the simulated pattern in the pool as a reference results in highest correlation of 0.91. The first (blue) cabled measurement appears to be more similar to the reference simulation but not necessarily to the other attempted cabled measurements. Alternatively in the case of optics the four measured pattern have correlation between 0.99-1.00 demonstrating excellent repeatability. The addition of the simulated pattern as a reference case, widens the range down to 0.95. The same is true for the second antenna of H1.

Finally it is worth noting that correlation computed in such manner is not necessarily a useful design metric. The influence of the incoming power distribution is discussed in [24] with additional details on user interaction in [20] and [25].

V. Conclusions

The paper compared practical results on different techniques for measuring correlation on small terminal devices. The focus is primarily on the lower GSM bands. It is shown that correlation measurements done with conductive coaxial cables are rather unpredictable and not very well repeatable. Similar conclusion is reached for the correlation computed from measured scattering parameters. It is shown however,

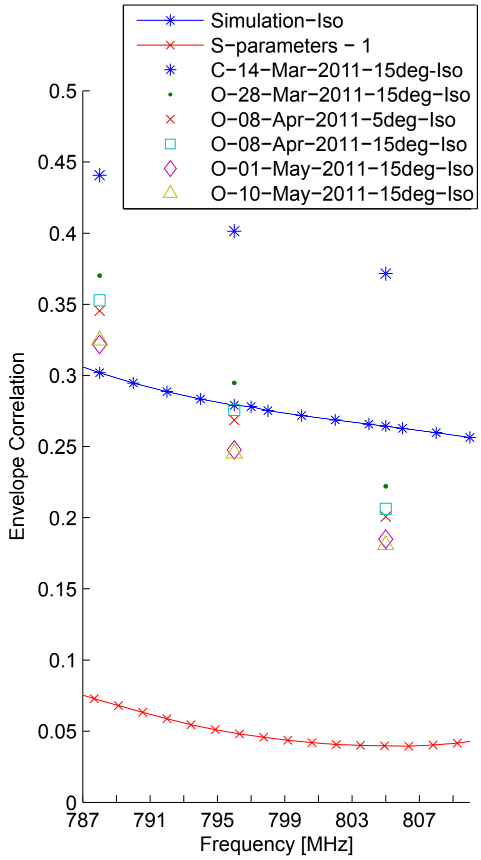

Fig. 4. Correlation in different cases for H6

that with the use of optical antenna measurement system, accurate and repeatable results can be achieved. The accuracy is very good when measuring highly correlated antennas and somewhat lower in the case of very low correlations. In all cases however, the optical system produces very well repeatable results, both short and long term, regardless of the radiation patterns sampling density.

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