Adaption of the Wheeler-Cap method for measuring the efficiency of mobile handset antennas

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ABSTRACT
In this paper an improved method for measuring the radiation efficiency of small devices is introduced. The method is based on Wheeler’s principle of measuring the antenna impedance within two controlled environments: free space and a closed metallic box. In addition to Wheeler’s network model, an extended equivalent circuit is introduced, that gives an exact description of the behavior of the small device within the metallic box. This model is the basis for the determination of the radiation efficiency, independent of the size of the box and the location of the device within the box.
Several measurements show, that using the new method, the radiation efficiency of mobile devices can be determined very fast and very accurately.

WHEELER’S METHOD
The radiation efficiency \( \eta_{rad} \) describes the losses within the antenna structure. It is defined by the ratio of the radiated power \( P_{rad} \) over the power \( P_{in} \) going into the antenna terminal [1]:

\[
\eta_{rad} = \frac{P_{rad}}{P_{in}}
\]  

(1)

The total efficiency \( \eta_{tot} \) includes also the return losses. It can be calculated from the radiation efficiency with respect to the reflection coefficient \( S_{11} \):

\[
\eta_{tot} = \left(1 - |S_{11}|^2\right) \eta_{rad}
\]  

(2)

Wheeler introduced a method for determining the radiation efficiency of antennas by performing two measurements, the first one in free space and the second one within a closed sphere [2] (Fig. 1). He assumes, that the antenna at resonance frequency can be modelled as two series resistances; the radiation resistance \( R_{rad} \) and the loss resistance \( R_L \). The first measurement delivers the sum of both contributions \( R_1 \), the second measurement delivers \( R_2 \), which corresponds to \( R_L \). The radiation efficiency can be calculated as [4]:

\[
\eta_{rad} = \frac{R_{rad}}{R_L + R_{rad}} = \frac{R_1 - R_2}{R_1}
\]  

(3)

Several investigations show, that one can obtain good results for electrically small antennas. However, all these investigations focus on antennas directly mounted on the ground plane, e.g. loop antennas or patch antennas [3][4]. Moreover, this approach is only valid as long as the inner losses of the antenna can be interpreted as a series resistance [3].

APPLICATION FOR SMALL DEVICES
Antennas of small mobile devices however do not use large ground planes. They are typically mounted on the top side or the back side of the mobile device, and the device acts as an active counter pole of the antenna [7]. Therefore, the whole device has to be considered in order to determine the radiation efficiency correctly.
Two samples of antennas mounted on small devices are built and measured using Wheeler’s method. The first sample is an 1800 MHz PIFA on a 100x40mm² PCB, the second sample is an
1800 MHz patch also on a 100x40 mm² PCB (Fig. 2). Losses are introduced by implementing a 10 Ohms resistance into the feeding pin of these antennas. Measurement 1 is performed by installing the device within an absorbing box. For measurement 2 the device is placed inside the metallic box, using a coaxial through connection. The efficiency is calculated using (3), considering only the real parts of the measured impedances:

\[
\eta_{rad} = \frac{\text{Re}\{Z_{rad}\}}{\text{Re}\{Z_{r}\} + \text{Re}\{Z_{rad}\}} = \frac{\text{Re}\{Z_{1}\} - \text{Re}\{Z_{2}\}}{\text{Re}\{Z_{1}\}}
\]  

(4)

Fig. 3. shows the results based on (4). The efficiency differs significantly for different sizes of the box and for different orientations of the device within the box. Also, the curves show strong minima at certain frequency points. From this we can conclude that the simple network model is not suitable for the determination of the radiation efficiency of mobile devices.

**IMPROVED MODEL**

One reason for the disturbances in Fig. 3. is the appearance of cavity modes within the shielding box [5]. Another important factor is obviously the size of the cap, that influences the result. The network model in Fig. 4 describes the function of the cap as a short circuit of the radiation resistance, however in practice it is not an ideal short circuit: the cap is lossy, and is located at a certain distance from the antenna (Fig 4).

Therefore, an improved model is defined (Fig 6), describing the cap as a small ohmic resistance \( R_{cap} \) connected via a transmission line. Its length \( l_{cap} \) describes the effective electrical distance between the device and the cap. \( R_{cap} \) is typically negligible when compared to the measured resistances. However, the transformed impedance at the antenna output port can become quite large depending on \( l_{cap} \). This is the reason for the steep nulls in the curves of Fig. 3, and it indicates clearly, that the effect of the cap distance cannot be neglected. In Addition, the series network for the antenna in Fig 1 is replaced by a more general description using a linear two-port-model.

Using this new equivalent circuit, the extraction of the efficiency is more complex. Johnston [6] describes a method to calculate the transmitted power by measuring the same antenna within several box dimensions, using a sliding wall. These measurements cause a circle in the Smith chart (Fig. 5), and the transmitted power can be directly determined:

\[
\eta_{tot} = |S_{21}|^2 = \frac{2}{(\Delta s_{\text{max}})^{-1} + (\Delta s_{\text{min}})^{-1}}
\]

(5)

According to Johnston’s approach, the circle can be obtained by varying the box dimensions. However, if we compare Johnston’s model with our new model of the antenna within the box, we can conclude, that the variation of the box dimensions is in fact a variation of the effective length \( l_{cap}/\lambda \). Therefore, the variation of the box length can be replaced by a frequency variation. This means, that the circle can be directly obtained by measuring over a certain frequency band.

This new model is now applied to the two mobile devices, using different box sizes and different orientations. The results in Fig 7. show that, by using the improved model, the radiation efficiency can be determined very exactly, independently of the size of the box and the position of the DUT within the box.

**CONCLUSIONS**

An improved method for measuring the antenna efficiency of mobile devices has been introduced. The method is based on Wheeler’s principle to determine the efficiency by measuring the antenna impedances. An improved equivalent circuit model is used to describe the effects of the box size and the orientation of the device within the box. Using this improved model, the radiation efficiency of mobile devices can be determined very exact.
REFERENCES


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**Measurement 1:**
- antenna
- groundplane

**Measurement 2:**
- "Cap"

Equivalent circuit:
- $R_L$
- $R_{rad}$
- $R_1$
- $R_2$
- $R_{rad} = 0$

**Fig. 1:** The wheeler method, measurement setups and network models

**Fig. 2:** test device (DUT) mounted on the ground plane

**Different box sizes**

**Different DUT orientations**
Fig. 3: Efficiency results for two mobile devices using the Wheeler method

Fig. 4: Mobile device within the wheeler cap. The distances between the device and the cap depend on the cap size and the orientation

Fig. 5: Extraction of the radiation efficiency from the measurement results

Measurement 1:  

Measurement 2:

Fig. 6: New equivalent circuits for the free space measurement (measurement 1) and the cap measurement (measurement 2)

Different box sizes

Different DUT orientations

Fig. 7: Efficiency results for the two mobile devices using the improved method