Experimental verification of broadband cloaking using a volumetric cloak composed of periodically stacked cylindrical transmission-line networks

Pekka Alitalo$^{1,2}$, Frédéric Bongard$^2$, Jean-Francois Zürcher$^2$, Juan Mosig$^2$, Sergei Tretyakov$^1$

$^1$ Department of Radio Science and Engineering / SMARAD Center of Excellence
TKK Helsinki University of Technology
P.O. Box 3000, FI-02015 TKK, Finland

$^2$ Laboratory of Electromagnetics and Acoustics (LEMA),
Ecole Polytechnique Fédérale de Lausanne (EPFL) Bâtiment ELB,
Station 11, CH-1015 Lausanne, Switzerland
Abstract

Cloaking using a volumetric structure composed of stacked two-dimensional transmission-line networks is verified with measurements. The measurements are done in a waveguide, in which an array of metallic cylinders is inserted causing a short-circuit in the waveguide. The metal cylinders are cloaked using a previously designed and simulated cloak that “hides” the cylinders and thus enables wave propagation inside the waveguide.
The reduction of an object’s total scattering cross section (SCS) from electromagnetic waves impinging on the object from arbitrary directions, often referred to as cloaking, has been the subject of many works in the recent literature after the publication of some seminal papers. The number of scientific papers devoted to the study of this phenomenon is already huge and therefore we will not review all the various cloaking techniques here, but instead, we suggest the reader to peruse the recent review paper by Alù and Engheta and the references therein. The cloaking phenomenon that is studied in this paper is achieved with the use of so-called transmission-line networks. This approach to cloaking has been studied analytically, numerically and experimentally in some of our recent papers.

In this paper, we experimentally demonstrate the cloaking phenomenon using a cylindrically shaped network of transmission lines. The “cloak” is a volumetric structure, composed of several two-dimensional networks that are stacked on top of each other. The cloak design that is used here was presented and studied numerically recently. A waveguide environment has been chosen here for the measurements since it allows to address the broadband behavior of the considered cloak through the measurements of reflection and transmission coefficients as functions of the frequency.

The cloak that is used here is periodic in the vertical direction (z-direction), with the dimensions of a single period as illustrated in Fig. The period of the network is 5 mm and the width and height of the transmission lines are shown in the figure. These dimensions have been found suitable for optimal cloak operation around the frequency of 3 GHz, by conducting full-wave simulations. The cloak is designed to work for TE-polarized waves with electric field \( E \) parallel to the \( z \)-axis. The cloak operation has been previously studied with full-wave simulations demonstrating the large bandwidth where the total scattering cross section of a two-dimensional array of metallic cylinders (the reference object that we want to cloak) is reduced. In these simulations all the metal objects such as the cloak itself and the cloaked object were modelled as perfect electric conductor (PEC) in order to reduce the simulation time. Cloaking with this type of device is not limited to two-dimensional arrays but works similarly also for three-dimensional objects, such as meshes. The only limitation is that the cloaked object must fit inside the cloak structure, i.e., within the space outside the transmission lines.
For the studied cloak structure, the cloaking phenomenon is first confirmed by conducting full-wave simulations with Ansoft HFSS\textsuperscript{10} of a cloaked and uncloaked object and calculating the far-field scattering cross sections for both cases.\textsuperscript{8} In these simulations the cloak is considered to be periodic and infinite along the $z$-direction. See Fig. 1b for the frequency dependence of the total SCS of the cloaked object, normalized by the total SCS of the uncloaked object (solid line). Fig. 1c presents the angular dependence of the scattering cross sections of cloaked and uncloaked objects at the frequency of 3.2 GHz. The data presented in Fig. 1c is normalized to the maximum value of the uncloaked object’s SCS.

The cloak shown in Fig. 1a was manufactured by etching from 200 $\mu$m thick metal sheets composed of bronze beryllium (BzBe). For stacking the cloak parts on top of each other, we use layers of dielectric foam (Rohacell) with relative permittivity $\varepsilon_r \approx 1.05$.

The measurements are conducted with a modified aluminium WR-340 waveguide, with the inner dimensions $435\text{ mm} \times 86.36\text{ mm} \times 36.8\text{ mm}$ (length $\times$ width $\times$ height). The height is determined by the fact that it must be a multiple of the cloak period in the vertical ($z$-) direction. In this case we use 4 networks on top of each other, i.e., $4 \times 9.2\text{ mm} = 36.8\text{ mm}$. Transmission through the waveguide is measured with standard coaxial probes with the distance from the waveguide (front and back) walls being 23 mm. The height of the probes also equals 23 mm. These values, with which good matching between the probes and the waveguide are obtained, were found with full-wave simulations of the empty waveguide.

The object that is supposed to be cloaked is a two-dimensional array of metallic cylinders that fits inside the cloak structure. The cylinders have a diameter of 2 mm and they are connected with the bottom and top walls of the waveguide to create a short-circuit inside the waveguide. See Fig. 2 for a photograph of the waveguide with the cloak and the metal cylinders inside.

The measured reflection and transmission for the empty waveguide are shown in Fig. 3, demonstrating that the empty waveguide section has low reflections and high transmittance for the frequencies of interest, i.e., around 3 GHz, where the cloak is supposed to work the best. With the uncloaked object inside the waveguide, the transmission is less than $-15\text{ dB}$ around this frequency. With the cloaked object, the measured transmission
and reflection agree well with those of the empty waveguide, especially in the frequency band from 2.5 GHz to 4 GHz.

The measurement results are in good agreement with the previous simulations of the cloak, experimentally confirming the broadband cloaking phenomenon also for real structures. As the fundamental mode inside the waveguide can be considered to be a sum of two plane waves with the incidence angles varying as functions of the frequency, these results also give further confirmation of the isotropy of the cloak. For comparison, also full-wave simulation results for cloaked and uncloaked objects inside the waveguide are shown in Fig. 3b.

The phase of the measured $S_{21}$ in the empty waveguide and the cloaked case are obviously different. For example, in the frequency range from 2.5 GHz to 3.3 GHz, the absolute value of the phase difference between these two cases varies between 0 and 45 degree. The envelope of the phase difference curve grows in magnitude with increasing frequency. This phase difference is due to the fact that the wave number inside the cloak is slightly different than in free space. As previously discussed and also demonstrated by Figs. 1b and 1c, in many practical situations this non-ideality does not prevent efficient cloaking.

We have presented a waveguide-based measurement procedure, with which we can, in a convenient way, study the cloaking phenomenon of certain types of cloaks. In this paper we have studied the performance of a volumetric microwave cloak composed of layered two-dimensional transmission-line networks. The broadband cloaking phenomenon, which has been studied before with numerical simulations, is now confirmed with measurements.

Acknowledgements

This work has been partially funded by the Academy of Finland and TEKES through the Center-of-Excellence program. During this work P. Alitalo was an invited researcher at EPFL-Switzerland. P. Alitalo acknowledges financial support by GETA, the Emil Aaltonen Foundation, and the Nokia Foundation.
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FIG. 1: (a) Cloak structure and dimensions in the $xy$-plane (top) and in the $xz$-plane (bottom). (b) Full-wave simulated total scattering cross section of the cloaked object, normalized to that of the uncloaked object. (c) Full-wave simulated scattering cross sections of uncloaked and cloaked objects at the frequency of 3.2 GHz. $\phi$ is the angle in the $xy$-plane and the plane wave illuminating the cloak travels to the $+x$-direction, i.e., in the direction $\phi = 0$.

FIG. 2: Photograph of the waveguide with the cloaked object and the cloak inside. The top wall of the waveguide is removed for clarity. The inset shows a magnification of the cloaked object enclosed by the cloak.
FIG. 3: Measured reflection (a) and transmission (b) for the empty waveguide (solid line), waveguide with the uncloaked object inside (dotted line) and waveguide with the cloaked object inside (dashed line). For comparison the full-wave simulated transmission corresponding to the uncloaked (squares) and cloaked (circles) cases are also shown in (b).