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Impact of RF Cables on the Electromagnetic Environment in Vehicles

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***Abstract*—As the demand for connectivity and infotainment services increases in the automotive world, the need to measure and characterize the propagation channels inside vehicles also increases. In this work, a measurement study was performed to investigate the influence of RF cables on in-vehicle channels. It was found that, for the same transmit and receive antenna positions, the routing of the measurement cables can significantly affect the channel impulse response. This result points to the need for alternative strategies or solutions to obtain accurate and repeatable in-vehicle channel measurements.**

***Index Terms*—vehicular communication, propagation channel, antenna measurements, cable influence**

I. INTRODUCTION

There is an increasing demand for integrating multiple wireless communication systems inside vehicles to facilitate wireless connectivity and infotainment services [1]. Popular examples are Bluetooth and wireless LAN hotspot. To ensure adequate quality of service, the design and implementation of these systems require careful characterization of in-vehicle wireless channels. Moreover, the proliferation of electronic systems inside modern vehicles has led to an increased level of electromagnetic interference (EMI) [2]. The ability to reliably characterize the channel provides engineers with an additional tool to address problems associated with EMI. An in-depth understanding of in-vehicle wireless channels is also critical to support the growing interest in replacing bulky cables with wireless connections [3].
To characterize in-vehicle channels, the first step is to perform accurate channel measurements, e.g., as reported in [1], [3]-[10]. In these studies, the antennas were placed at multiple locations inside the vehicle cabin to measure the channel impulse responses for a given transmitting antenna location. Typically, the measurement setup is calibrated with respect to the specific radiofrequency (RF) cables used, to compensate for cable induced losses and phase shifts [4], [5]. However, little attention is paid on the exact routing of these cables and cable effects on channel measurements.

In the context of terminal antennas, measurement cables are known to introduce significant errors in antenna and channel measurements [11], [12]. However, the influence of the cable in these cases is mainly due to electrically compact antennas and cable routing that disturb the currents and the near-fields. In the case of vehicular antenna and channel measurements, the common use of well-behaved reference antennas (e.g., dipoles with baluns and monopoles) limits cable effects due to near-field disturbances. However, the metallic RF cables has the potential to interact with the electromagnetic fields illuminated by the transmitting antenna, especially when they are in the vicinity of the antenna [8]. In other words, they can become effective scattering objects in the propagation channel. Even though it is a standard practice in channel measurements to route the cables to avoid regions of strong fields [5], the nearly enclosed space inside the vehicle and the reverberation of the propagating waves greatly increase the likelihood of an in-vehicle object being illuminated as a scattering object.

In this paper, we investigate the influence of RF cables on in-vehicle channels through channel measurements. Two sleeved dipoles and a monopole with the center frequency of 900 MHz were used. The transmitting antenna location was fixed, whereas the receiving antenna was placed at different locations. For each receiving antenna location, different cable routings were used to study the cable influence. Consistent to the hypothesis that the in-vehicle channel is susceptible to cable influence, it was found that the exact cable routing has a significant influence on the measured channels. To verify this observation, full-wave electromagnetic simulations that replicate some of the measurement scenarios were performed. The results confirm that significant cable influence is also present in the simulated channels. This work highlights the importance of proper guidelines or best practice for cable routing when performing in-vehicle channel measurements.

II. MEASUREMENT AND SIMULATION SETUPS

A. Measurement Setup

The in-vehicle channel measurements were performed on a real, fully-equipped Volvo XC60. The

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car has a sun roof (closed during the measurements) and it is equipped with standard features such as wall panels, a dashboard, floor boards and seats. To mitigate external electromagnetic disturbances, the measurements were carried out in an anechoic room. A two-port vector network analyzer (VNA) was used to measure the coupling coefficient (channel transfer function) between the transmitting and receiving antennas. The measured frequency range was 860-940 MHz (i.e., where the reflection coefficients of the antennas were below -10 dB), and 401 uniformly spaced frequency points were measured. The VNA was calibrated to account for the phase shifts and losses in the RF cables and connectors. The location of the transmitting antenna (half-wave sleeved dipole with balun) was fixed, and it was located below the rear seat. The receiving antenna was placed at three locations: 1) Above the rear seat, mimicking the location of a mobile phone held to the head by a rear-seat passenger, 2) At the rear quarter glass, where a TV antenna would normally be placed, and 3) On the roof, near the common location of the shark fin antenna. A sleeved dipole of the same type as the transmitting antenna was used in receiving locations 1 and 2, whereas a monopole was used in location 3. Figure 1 shows the locations of the transmitting and receiving antennas, with the receiving antenna placed at location 1. Locations 2 and 3 of the receiving antenna are depicted in Figs. 2 and 3, respectively. The RF cable for the transmitting antenna was routed into the car through the open front-right window, whereas the cable for the receiving antenna at locations 1 and 2 was routed through the open rear-right window. The rear-right window was closed for receiving location 3. For each receiving location, the channel was measured for several receiving RF cable routes, to investigate cable influence. For some cable routes, the length of the cable inside the car was also varied. The cable routing for the transmitting antenna was kept the same in all the measurements. In the vicinity of the antennas, the cables were oriented to avoid near-field disturbances.

B. Simulation Setup

To verify the cable influence observed in the channel measurements, full-wave simulations were performed using the time-domain solver of 2016 CST Microwave Studio. A three-dimensional (3D) perspective of the rear section of the simulated car model is shown in Fig. 4. The original CAD model of the Volvo XC60 from the car manufacturer came with many fine details that were considered irrelevant to the electromagnetic environment of the main car body at around 900 MHz (e.g., interior decorations, sealing, welded nuts). Moreover, in [13], it was found that most of the dielectric materials (foam and plastics) in the interior of a vehicle do not have a significant impact on the electric field distribution inside the vehicle for frequencies up to 2 GHz. Therefore, these details were removed to reduce the mesh size.

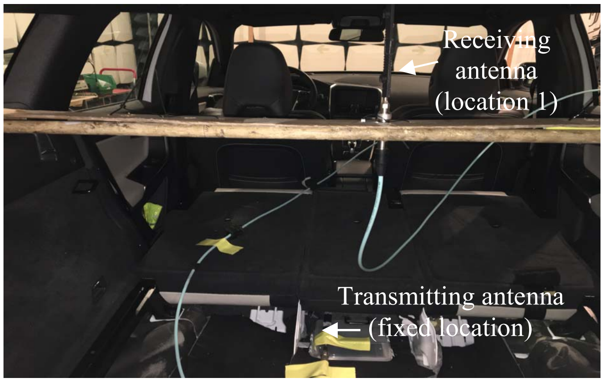

Fig. 1. Transmitting antenna below the rear seat and receiving antenna above the rear seat (receiving location 1).

Fig. 2. Receiving antenna at the rear right quarter glass (receiving location 2).

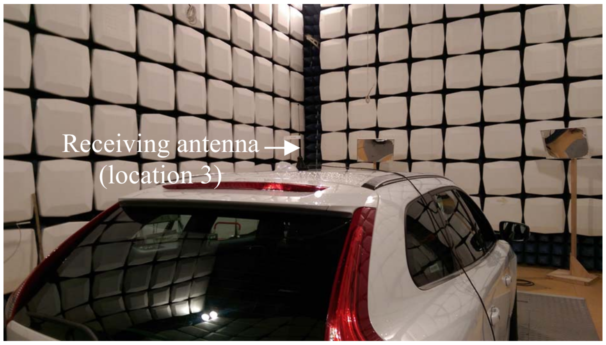

Fig. 3. Receiving antenna on the roof (receiving location 3).

However, the glass materials (windscreen, rear screen and side windows) that were found to be important for simulation accuracy [13] were kept in the simulations. Large metal parts in the seats were also simulated, as they have substantial impact on the electromagnetic fields inside the vehicle [14], [15]. All metallic parts in the simulation model were given the properties of perfect electric conductor (PEC). Using the manufacturer's data, the relative permittivity of the glass was set to 6.8 and the loss tangent to 0.025, which are close to the values in [13]. Ideal half-wave dipoles and a quarter-wave monopole with similar radiation properties as the real dipoles and monopole were used in the simulations.

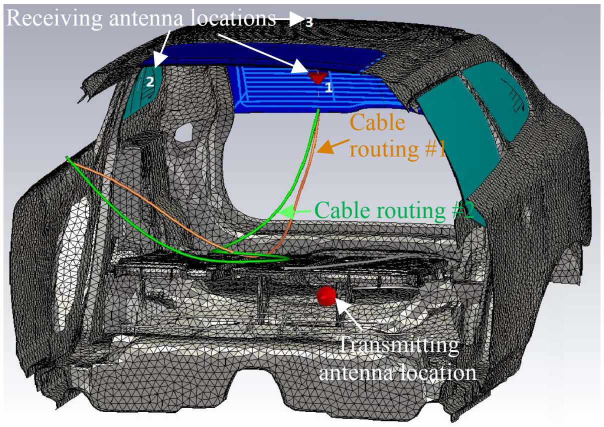

Fig. 4. 3D view of the simulated model (rear part) shown with all the locations of the antennas. Two cable routings are also shown for receiving location 1.

III. RESULTS AND DISCUSSIONS

A. Measurements

For the receiving antenna at location 1 (above rear seat), the channel was measured for four different cable routings (see Fig. 5). The measured result shows variations of 0.5-17 dB in the channels with different cable routings, despite that the cable was consistently left hanging downwards (orientation with minimum field disturbance) in the vicinity of the receiving antenna. This phenomenon highlights the role of the in-vehicle reverberation environment [9] in creating a fading environment where the cable (a scattering object) interacts with multiple regions of strong electric fields to result in a modified field distribution [8], [16]. Similar reverberation effects were also identified inside a bus [8] and an aircraft [9]. In other words, the different cable routings inside the car acted as unique mode stirrers in the "reverberation enclosure" to create different scattering environments and field distributions.

To further ensure that the variations in the measurements were caused by different cable routings instead of measurement uncertainty, the repeatability of the measurement was studied. The measurement setup for receiving location 1 was reproduced 6 times for one cable routing and the measured channels are plotted in Fig. 6. For each repeated measurement, the receiving antenna and its cable were first disconnected and removed from the car. Then, they were reconnected and restored to the original locations. It can be observed that measurement uncertainties only contribute to minor variations in the channel (of up to 1 dB) for most of the frequencies.

Different cable routing measurements were also performed for the other two receiving antenna locations: at the quarter glass (location 2) and on the roof (location 3). Two different routings were considered in each case. The results are shown in Figs. 7 and 8, respectively. For the quarter glass location (see Fig. 7), large variations (of up to 10 dB) in the results can again be observed, indicating that the different cable routings change the field distribution significantly at the quarter glass.

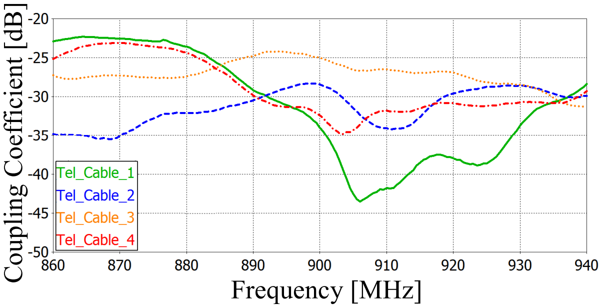

Fig. 5. Measured channel (coupling coefficient) with four different cable routings for the receiving dipole antenna above the rear seat (location 1).

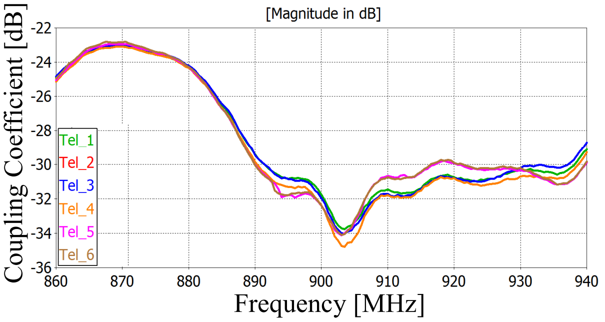

Fig. 6. Repeatability measurements for the receiving antenna above the rear seat at location 1. The same cable routing was reproduced in all cases.

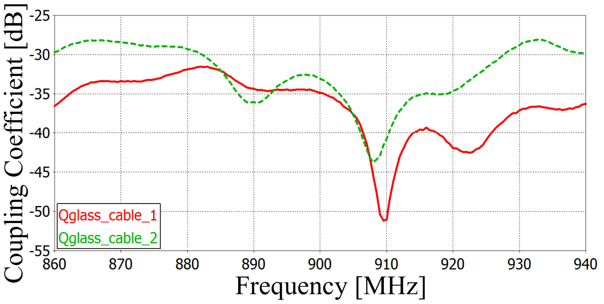

Fig. 7. Measured channel with two different cable routings for the receiving antenna at the rear quarter glass (location 2).

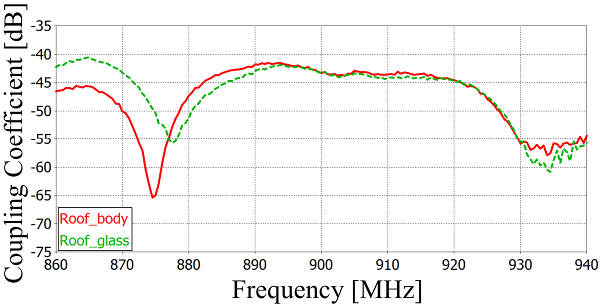

Fig. 8. Measured channel with two different cable routings for the receiving antenna on the roof (location 3).

The results for the roof top location (see Fig. 8) show much less variations as compared to the other two receiving locations. The variations are mostly confined to the region below 890 MHz. This is due to the roof antenna being placed outside of the vehicle cabin and the cables are routed close to the outer body of the car. Therefore, the impact of the cables is reduced. The main difference in the two cable routes is that the cable is routed across the rear right quarter glass in one case, whereas it is routed along the metallic car body in the other case to minimize disturbances to the field distribution.

B. Simulations

To verify as well as analyze the impact of the cables as seen in the measurements, full-wave antenna simulations were performed for receiving locations 1 and 3 based on the simplified car model described in Section II-B. Two different cable routings in the measurements (for the receiving antenna) were reproduced in simulation using a solid PEC wire with the same diameter as the real RF cable (see Fig. 4). The wire is terminated at the side window.

For the receiving antenna at location 1, the simulation results are shown in Fig. 9. The case of no cable at the receiving antenna was also simulated for location 1, since in reality there is no cable connection to the mobile phone antenna. The results confirm that large variations in the channel (of up to 10 dB) can be attributed to different cable routings. The figure also shows that the very presence of the cable (not just the routing) has a large influence on the measured channel, especially since the measured location in this case requires the cable to be exposed in mid-air.

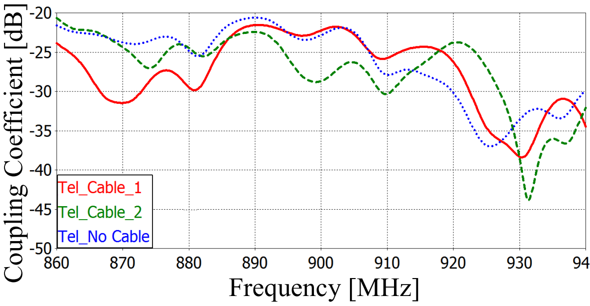

Fig. 9. Simulated channel (coupling coefficient) with 2 different cable routings for the receiving antenna above the rear seat (location 1).

It should be noted that the results from the simulation study are not intended for absolute comparisons with the measured results. This is because the simulation models of the car and the cables are simplified versions of the real structures. Moreover, the sensitivity of the channel to the exact routing of the cable further complicates the exact reproduction of measured results. Nevertheless, the corresponding simulated and measured channels for one of the cable routings for receiving location 1 (see Fig. 10) show reasonable agreement. Apart from the region in the vicinity of 930 MHz, the discrepancies between the results are within 3 dB.

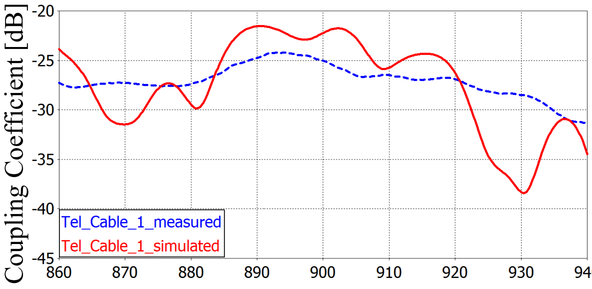

Fig. 10. Simulated and measured results for one of the cable routings for the receiving antenna above the rear seat (location 1).

The simulated channels of two different cable routings for receiving location 3 is presented in Fig. 11. The two cable routings were similar to those used in the corresponding measurements (routing across the rear right quarter glass vs. routing along the car body). The larger channel variations occur at lower frequencies, similar to the trend observed for the measured channel in Fig. 8. However, the simulated and measured channels are quite different in absolute terms, and this could be due to the difficulties in modeling the glass accurately. In particular, metallic meshes are embedded in both the wind screen and rear screen for heating purposes. Such composite structures are difficult to model precisely for electromagnetic simulations.

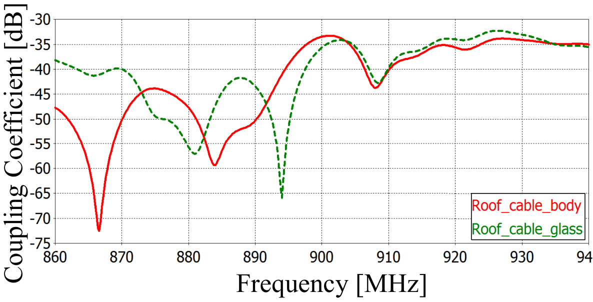

Fig. 11. Simulated channel with 2 different cable routings for the receiving antenna on the roof (location 3).

To further substantiate the claim that RF cables have a significant impact on the channel (and hence the field distribution) inside the vehicle, simulated field distributions are shown in Figs. 12-14 for the three cases shown in Fig. 9 (two different cable routings and no cable). The electric field distributions are presented for the vertical plane containing the receiving dipole at 913 MHz, along the length of the car. As can be seen, the field distributions in Figs. 12 and 13 show both high and low field regions around the cables, and the distributions are substantially different around the receiving antenna as well as in the rest of the cabin. Similarly, the field distribution for the no-cable case shown in Fig. 14 is also significantly different from the cases with RF cable. The magenta circles highlight several regions with significantly different electric field distributions across Figs. 12-14.

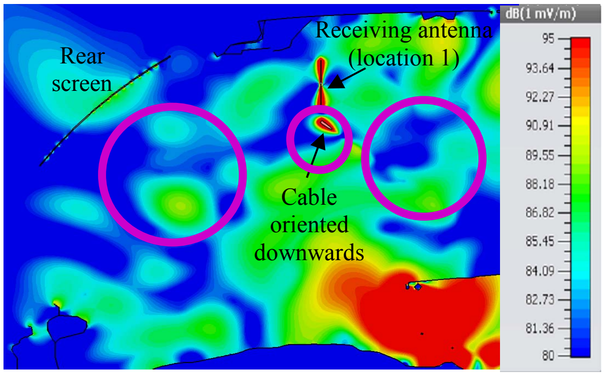

Fig. 12. Electric field distribution along a vertical plane inside the car with the first cable routing for the receiving antenna above the rear seat (location 1).

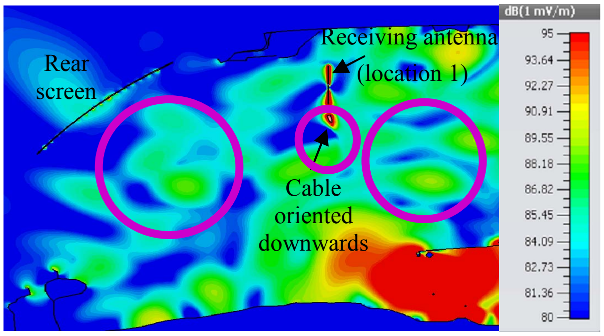

Fig. 13. Electric field distribution along a vertical plane inside the car with the second cable routing for the receiving antenna above the rear seat (location 1).

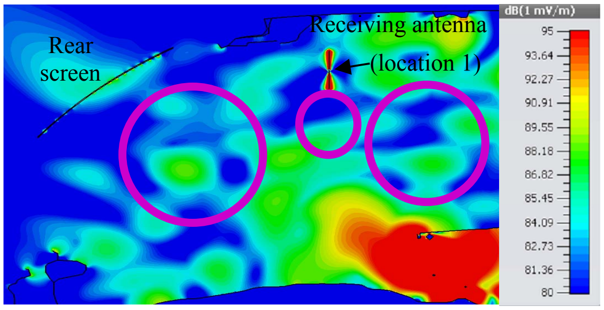

Fig. 14. Electric field distribution along a vertical plane inside the car with no cable modeled for the receiving antenna above the rear seat (location 1).

IV. CONCLUSIONS AND RECOMMENDATIONS

A lot of effort is being put into understanding the properties of in-vehicle wireless channels, in order to design efficient, reliable and robust wireless communication systems for vehicles. In this work, we investigate the influence of the RF measurement cables on the accuracy of in-vehicle channel measurements. Measurements and full-wave simulations for several scenarios with fixed antenna locations and different cable routings were performed. It was found that in many cases, different cable routings resulted in over 10 dB of differences in the channel. This difference is also reflected in the different simulated in-vehicle electric field distributions.

Given the significant influence of RF cables on in-vehicle channel measurements, as concluded from both measurements and simulations, it is important to apply special measures to minimize this effect. In the electromagnetic compatibility (EMC) community, a standard measure is to attach the RF cable to the metallic frame of the vehicle. This measure reduces the impact of the cable as a standalone scattering object. This is also the current industrial practice for the packaging of installed vehicular antennas in manufacturing and production. However, it is not possible to achieve this when performing in-vehicle channel measurements or similar measurements when the transmitting or receiving antenna is not positioned near the car body. Therefore, it is not possible to completely remove the cable effects in this case. Another countermeasure is to place filters or ferrites at regular intervals along the measurement cable, to mitigate induced currents along the cable [11]. In the case that the presence of the cable does not reflect the real channels (e.g., the mobile phone antenna case at location 1), the RF cable can be replaced by optical cables through the use of radio-over-fiber (ROF) solutions [12].

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