Exploring a cost-effective approach for digital radio broadcasting (DAB+) service coverage inside tunnels.

B. Sacco, A. De Vita*
Centre for Research, Technological Innovation and Experimentation, RAI - Radiotelevisione Italiana, Torino, Italy
[*] Corresponding author: assunta.devita@rai.it

Abstract: The achievement of a satisfactory coverage of Digital Audio Broadcasting (DAB+) service, in the VHF band, inside tunnels is a very challenging task. The classic –but expensive-solution is the use of radiating cables ("leaky feeders") installed on the tunnel's ceiling for the whole length. An alternative and cheaper solution, studied in the present paper, is the "direct RF radiation" approach, by means of antennas placed inside the tunnels or just outside the gallery's entrance. In particular, a simulative analysis has been carried out, to evaluate the impact of the design parameters, but also to serve as a tool for estimation of the achievable service coverage. By means of COMSOL Multiphysics® and the LiveLink™ for MATLAB® module, the full tunnel has been simulated as a sequence of short segments. In post processing, the results are joined together to get the complete behaviour of the field propagation along the tunnel. Interesting outcomes have been obtained from this preliminary analysis, suggesting a helpful guidance for the design of direct RF radiation installations for DAB/DAB+ services.

Keywords: COMSOL Multiphysics; LiveLink for Matlab; Motorway Tunnels; Digital Audio Broadcasting (DAB) service; Very High Frequency (VHF) band, Finite Element Method (FEM), Direct RF radiation.

1. Introduction

For decades, in collaboration with the main Italian motorway licensees (ASPI, ADF, AdP), RAI has provided a special radio programme for motorways called "Isoradio", based on a single FM frequency (103.3 MHz), the tunnels being served by means of radiating cables ("leaky feeders") installed along the ceiling. Such a solution ensures good FM service continuity in the frequency bands around 100 MHz, even in heavy traffic conditions. However, due to the cable loss and attenuation, intermediate amplification for trunks longer than 1 km is necessary. Therefore, while tunnels up to 2 km could be fed by external amplification systems, very long tunnels will require several cable trunks and internal signal repeaters. It should be considered that the installation of new radiating cables is expensive; furthermore, even in tunnels already installed with radiating cables and in use for other radio systems (e.g. police, mobile telephony, radio alerts...), the introduction of additional signals on different frequencies requires expensive adaptations.

Preliminary field tests, where the RF signal is received in tunnels from nearby external broadcast transmitters, have confirmed the well-known difficulty of ensuring a fair quality of service in tunnels. As an alternative and cheaper approach to the "leaky feeders" solution, "direct RF radiation" is currently under investigation by means of antennas positioned near tunnel's entrance, either internally or just outside it. To evaluate the feasibility of this solution, test measurement campaigns have been carried out by RAI in cooperation with ASPI (Autostrade per l'Italia) and documented in [1]. As expected, field tests have shown that the coverage strongly depends on the tunnel's geometry, the transmitter's antenna position, its aiming and polarization. Therefore, a simulative approach is desirable, to investigate the impact of the design parameters, but also as a tool for estimating the service coverage achievable in specific cases.

Figure 1. "Direct RF radiation" with antennas positioned outside gallery's entrance.

By means of COMSOL Multiphysics®, a tunnel segment has been modelled, parametrized in terms of section geometry, length, curvature radius, and electromagnetic surface parameters. However, for the FEM simulation, the maximum length of the segment is limited by the available computer memory. Therefore, using the LiveLink™ for MATLAB® module, the full tunnel has been simulated as a sequence of short segments. In post processing, the results from each run have been linked to get the complete behavior of the signal propagation inside the tunnel.

Simulations have been performed using the geometry of the motorway tunnels investigated in the field tests (reported in [1]), to provide a useful comparison between measurements and simulations results.

From the preliminary analysis carried out in the present paper, a good agreement between numerical analysis and field test has been proved. The simulation outcomes provided useful information for the design of direct RF radiation installations for DAB/DAB+ services.

2. FEM simulation of a typical motorway tunnel

In general, several modeling approaches can be adopted for radio signals propagation prediction in tunnels, namely: numerical techniques for solving Maxwell equations, waveguide or mode analysis, ray-tracing based methods and so on [2]. Among the different numerical methods solving Maxwell equations in differential form, the FEM approach is especially useful for arbitrarily shaped tunnels but it requires a large amount of computer memory (which depends on the volume of the model in relation to the operating wavelength) and consequently a long computation time to solve the final matrix equation. A typical three-lane motorway tunnel (like the one considered in the present analysis) has a rather large section, consequently the length of the tunnel segment that can be simulated at one time is very short. To overcome the problem, it is possible to consider a tunnel of any length and operate a segmentation into portions of reduced length, each characterized by its local (constant) radius of curvature. A basic tunnel segment model, with appropriate parametrization of the geometry's section, length of the segment, and radius of curvature, has been designed (Figure 2).

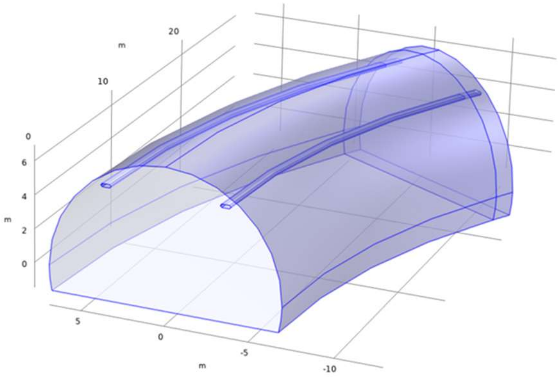

Figure 2. Parameterized tunnel segment model.

It is also easy to model some details such as the metal conduits located on the vault of the tunnel. The vault and the road surfaces are represented by boundary conditions representing an infinite half-space of homogeneous and isotropic materials whose electromagnetic properties are described by relative dielectric constant, relative permeability, and conductivity [S/m]. Identifying the values of these three parameters at the frequency of interest is a non-trivial problem. However, based on a wide range of works available in literature [3,4], satisfactory values were identified. In particular, Epsr=5.5, Mur=1, Sigma= 0.03 [S/m] were used both for the vault and the street level. Furthermore, it has been assumed that the tunnel maintains its cross-sectional geometry unchanged, and the electromagnetic parameters of the constituent materials are also constant, homogeneous and isotropic throughout the whole tunnel length.

The tunnel's segmentation described above requires the exact knowledge of the local curvature radius for the entire gallery's path. As this information is not easily available, using Google Maps, the route between the entrance to the tunnel of interest and the corresponding exit was derived; the layout was then saved and exported in KML format. From the generated ASCII file, the table containing a sequence of coordinates (latitude, longitude) can be easily extracted. To build a file in tabular format containing the radii of curvature with the correct step (defined in terms of curvilinear abscissa) a suitable code was written. Such program receives the above table as input, converts it into meters (in Cartesian coordinates), calculates the increments and then the distance on the curvilinear abscissa, interpolates and resamples with the required segment step, and finally calculates the radii of curvature for each step.

3. Generalization with COMSOL LiveLink for Matlab

As mentioned before, the simulative analysis of the whole tunnel has been carried out using the COMSOL module LiveLink™ for MATLAB®, which basically extends the COMSOL modeling environment with an interface between COMSOL Multiphysics® and MATLAB®. Therefore, since COMSOL Multiphysics integrates with MATLAB via the LiveLink for MATLAB, it is possible to generate a MATLAB file version of a simulation built with COMSOL Multiphysics, modify the model MATLAB file, extend it with MATLAB code, and run it from MATLAB. In this specific case, the whole tunnel has been expressed as a sequence of segments each having its own radius of curvature. The global simulation is carried out in sequence: the field distribution at the input is loaded, and then first segment is simulated with FEM to obtain (and hence save on disk) the field distributions on the internal path and on the output surface. The field distribution of the latter will constitute the input excitation of the subsequent segment. The loop is continued up to the end of the tunnel. Finally, the saved internal field distributions are joined to obtain the whole field map. Depending on the use case we wish to investigate, namely the external or internal antenna, the field distribution at the entrance of the first segment is obtained either from a previous simulation of a model that contains the transmitting antenna (Figure 3), or analytically (e.g.: hypothesis of an oblique plane wave coming from outside). In this second case the strength of the incident electric field can be estimated with the Friis' formula.

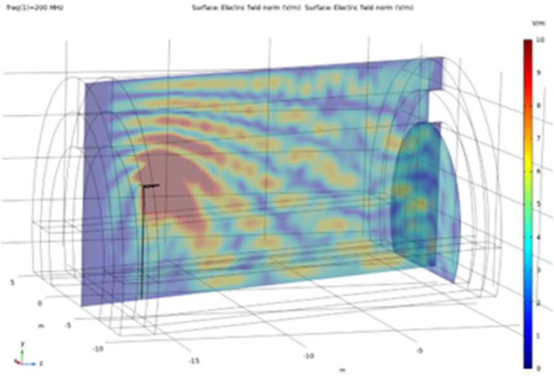

Figure 3. Transmission from external antenna.

A simple flow chart describing the algorithm implemented in LiveLink for Matlab is reported in Figure 4.

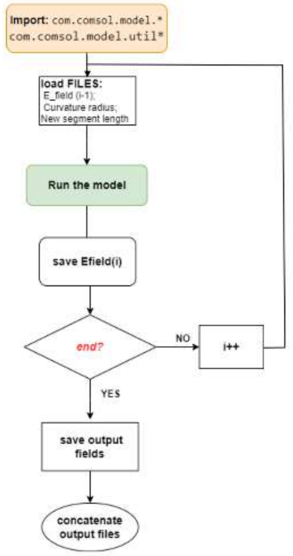

Figure 4. Process flow chart adopted for the COMSOL model.

4. Mode analysis of the tunnel section

In principle, it is possible to assimilate the tunnel geometry to a hollow waveguide although with some limitations due to the fact, for instance, that the walls are not perfectly reflecting surfaces as in the case of metal waveguides commonly used as transmission lines in microwave applications. However, the idea to associate the tunnel with a waveguide has some advantages: indeed, at the frequencies of interest for the present analysis, the cross section of the gallery has dimensions (much) greater than the wavelength: therefore, the theory guarantees that there are several different field configurations ("modes") that propagate. Each mode has its own propagation constant and propagates in the longitudinal direction independently of the other modes. The fundamental mode will have less attenuation per unit distance; higher order modes will present increasingly larger attenuations. Consequently, as the distance increases, we can expect that the higher-order modes vanish, and thus that the transverse field distribution turns out to be smoother. All this is true under the assumption that the section remains orthogonal to the waveguide axis. Unfortunately, in the curved tracts of the tunnel this is no longer guaranteed: it may therefore happen that the modes no longer propagate independently, but part of the energy transported by each one is redistributed among the others. However, for the straight tracts of a tunnel, the attenuation constant of the fundamental mode provides a good indication of the attenuation behavior of the wave component having the associated polarization. The other polarization will typically be associated with the second mode, and it is therefore possible to obtain the attenuation performance from this. As it can be seen in Figure 5, the fundamental mode (top left) conveys basically a horizontal polarization; the second one (top right) a vertical polarization. In all the other modes, the electric field vector assumes a highly variable inclination from point to point. When analyzing the effect of the individual modes on reception, it must be taken into account that the antennas of the passing vehicles are located at a certain height from the road surface and that they may be in the first, second or third lane. As a consequence, the received field level will vary accordingly.

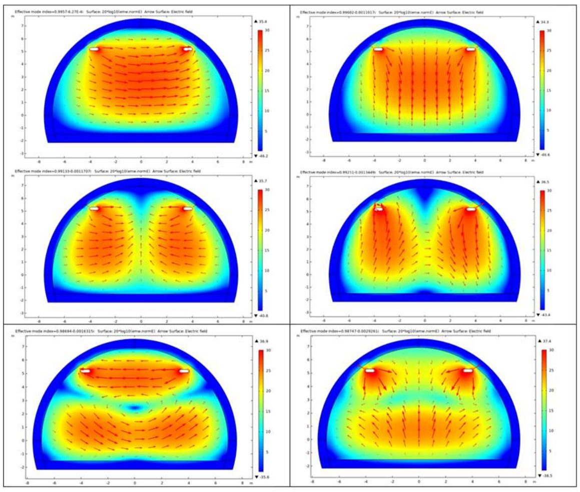

Figure 5. Field configurations of the first six modes.

5. Characterization of the antenna used in field measurements

In the field measurement campaigns aimed at assessing the coverage of radio services, the evaluation of the electric field is typically obtained by measuring the level of the signal received downstream of the antenna[1], and hence the field value is obtained using the antenna factor which is in turn calculated starting from the antenna gain. A vertical whip antenna mounted on a vehicle is often considered equivalent to the vertical dipole. However, its diagram can be different, mainly for two reasons:

- the roof of the car is a reflection plane of limited extension;
- the presence of the ground which, constitutes a further reflection plane (with losses).

Furthermore, in the field tests, the measurements had been carried out using three antennas on the roof of the vehicle.

The evaluation of the "effective" antenna factor, in the complex situation of a $\lambda/4$ monopole mounted on the roof of the vehicle, in the presence of two other antennas at a short distance, would require the availability of an accurate CAD model of the vehicle.

Having only the CAD model of a different vehicle available, a first attempt of simulative analysis with a single antenna was made, scaling the vehicle model in anisotropic manner in order to give it the same overall dimensions as the vehicle actually used (Fig.6). By doing this, however, the roof does not have the same dimensions and curvature. The simulation result therefore only gives us a rough idea of the actual antenna gain. In these conditions the gain at low elevations would be around -1.5 dBi: this value was also confirmed by simulating a flat metal rectangle, having the same dimensions as the car's roof, with a single antenna.

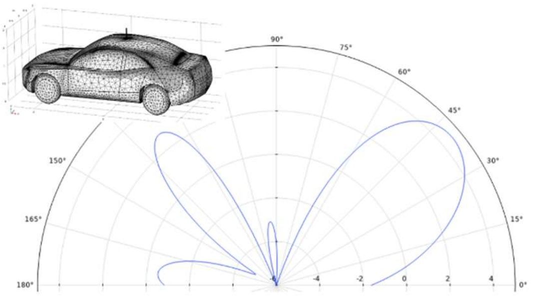

Figure 6. Single monopole on the car's roof and corresponding radiation pattern section in sagittal plane.

Finally, the configuration with the three antennas on the metal plane, positioned as in the measurement campaign, was also simulated (Fig. 7). The second antenna was identical to the first, while the third was for FM reception, and was described as a high impedance, $\lambda/2$ monopole. From the above simulations, it resulted an effective gain at low elevation of -3 dBi for the back direction and -1 dBi for the forward one.

These results allowed us to improve the accuracy of the field measurement data.

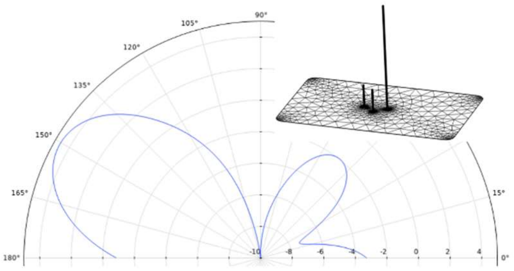

Figure 7. Three antenna's system adopted in test fields and corresponding radiation pattern section in sagittal plane.

7. Comparison between simulations and field tests

The results obtained from the COMSOL simulations of the Puliana tunnel signal coverage have been compared with the measurements performed during the tests [1] along the Apennine trunk of the A1 motorway between Bologna and Florence (Puliana tunnel). Fig.8 shows an excellent agreement between tests and simulations (green line).

It is worth noting that the average slope of the straight tract (47 dB/km) is in line with the mode analysis for the vertical polarization (45.9dB/km).

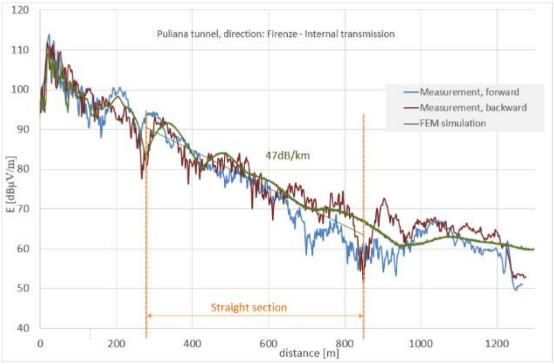

Figure 8. Comparison between test measurements and simulations. The tunnel is 1310 m long; a straight tract is indicated in orange.

8. Conclusions

The most relevant results that can be derived from the present analysis are summarized in the following points:

---

[1] Taking into account the possible attenuation of the cable.

- As known in literature, the behaviour of the electric field as a function of the distance in tunnels exhibits a *near* zone, in which the slope of the curve is steeper, followed by a *far* zone in which the slope is less accentuated.
- We have found that, in the absence of geometric perturbations, the slope in the far zone is in good agreement with the attenuation value per unit distance of the main propagation mode (for the relevant polarization), obtained from the mode analysis.
- Curved tracts cause a further attenuation which depends on the radius of curvature. This is one of the more complicated aspects of the problem.
- For tunnels with an arched section the fundamental propagation mode is horizontally polarized. As a result, the typical "whip" vehicular receiving antenna is not adequate; a horizontally polarized antenna would provide much better service inside tunnels.
- The geometric dimensions of the tunnel section, on the other hand, have a very strong impact on the attenuation. This is clearly evident from the modal analysis.
- While the curved sections add an important attenuation to the wave that propagates along the tunnel, from the comparison of the graphs obtained from field measurements with those of FEM simulations, it turns out that the actual presence of objects and sporadic geometric anomalies (niches, annunciator panels, etc.) do not introduce significant attenuations.

6. References

[1] A. Morello, S. Ripamonti, M. Tabone, G. Vitale "DAB+ Signal Propagation in Tunnels," EBU Tech. Report, March 2017 – Geneva.

[2] L. Deryck, "Natural propagation of electromagnetic waves in tunnels," IEEE Trans. on Vehicular Tech. vol. 27, NO. 3, pp. 145-150, August 1978.

[3] Y. Yamaguchi, T. Abe, T. Sekiguchi, J. Chiba, "Attenuation Constants of UHF Radio Waves in Arched Tunnels" IEEE Trans. on Microwave Theory and Tech. vol. MTT-33, NO.8, pp. 714-718, August 1985.

[4] S. Jiping, C. Lingfei and L. Xiaoyang "Influence of Electrical Parameters on UHF Radio Propagation in Tunnels," *Proceedings of IEEE 10th Asia-Pacific Conference on Communications and 5th International Symposium on Multi-Dimensional Mobile Communications,* Beijing - China, 2004.

7. Acknowledgments

The authors would like to thank the whole COMSOL technical support staff in Brescia, Italy, with particular regard to Gabriele Rosati and Cesare Tozzo, for the useful discussions and suggestions. The authors wish also to thank the colleagues Giovanni Vitale (RAI) and Danny Noferi (ASPI) for their important support in providing details on the measurement campaign of DAB+ services in the early phase of the work.