Near-field coupling of wireless devices and long communications cables

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Abstract: A comprehensive investigation of the coupling between mobile devices and communication/control cables in several environments is described here. Both experimental and numerical results are shown and compared using a number of different methods in different laboratories. Results indicate a good level of agreement between the different approaches thus giving confidence that predictive studies based on simulation can give a good quantitative assessment of coupling. Moreover, the studies show that varying the configuration of the coupled systems does not significantly affects the maximum coupling thus making it possible to obtain a reasonable worst case estimate of coupling from a small number of generic studies.

1 Introduction

Over the last two decades, mobile phones have evolved from simple single-channel two-way radios and text messaging devices to advanced multifunctional multimedia and entertainment marvels [1–3]. In recent years, wireless communication has experienced an explosive global growth. Along with the industry transitions from second generation to third generation (3G), considerable worldwide interest in the development of nomadic wireless devices brought about a new generation of 3G mobile phones and related networks [2]. The new generation mobile phones not only support the basic voice service in multiple frequency bands, but also support high-speed data, multimedia applications, global positioning system location technology and Bluetooth wireless connectivity [2]. The excitement generated by the prospects of these new devices is tempered by concerns over their impact on the electromagnetic (EM) noise floor of environments densely populated with such devices, and concerns over their direct coupling to, and possibly malfunctioning of, other devices, such as control, sensor and communication devices interconnected through long cables and wires [4–6]. It is highly desirable to assess the level of coupling between such systems and therefore offer the capability to designers of estimating the risk of malfunction and the effectiveness of proposed remedies using computer-aided design tools.

The COST 286 (EMC in diffused communications systems) management committee set up a joint technical action to address this issue and establish the efficacy and accuracy of predicting the level of EM coupling between generic mobile devices and long cables. The objective of this work was to approach this problem using a number of different simulation techniques, such as method of moments (MoM), finite-difference time-domain (FDTD), transmission-line modelling (TLM), applied in a number of different European Laboratories, in parallel with the conduct of experiments in different locations using locally constructed experimental set ups. Results were then compared to establish the variability to be expected when several researchers have addressed nominally the same problem, but using their own techniques and methodologies. This was not only simply an exercise in comparing different modelling methods or software, but also of the way that skilled users employ these tools. Similarly, the objective was not only simply to see whether the simulations can reproduce the experimental results, but also whether the experiments were sound and well controlled. In the course of this investigation, we were able to identify cases where errors had influenced both simulations and measurements without at first sight being obvious to the user. The synergetic use of simulations and measurements by a number of users gave us a valuable insight as to how to measure and model accurately. The results of this work are presented in this paper. Ultimately, the question to be answered is whether given the complexity of modern systems, where a mobile device can be placed at different locations, polarisations, with/without people being present, any useful conclusion may be reached on the level of coupling to a long cable. If the answer is affirmative, then a user can obtain a useful insight and quantitative estimate on the strength of coupling from a small number of studies to inform design. Results reported here show that this is indeed the case.

doi:10.1049/iet-smt:20070012

Paper first received 5th February and in revised form 19th June 2007

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The generic problem deals with the coupling of a near-field radiating dipole antenna into the cabling of a system, within a restricted space. The scenarios or configurations of the problems to be presented and discussed in this paper are mainly comprised into two stages: firstly, a thin wire above a ground plane in an open area; secondly, a thin wire in an enclosure with and without the presence of passengers.

The first problem, that is, a thin wire above a ground plane in an open area, has been simulated independently by different groups of researchers with different numerical methods, and EM simulation packages, such as the MoM-based MoM/NEC, MoM/CONCEPT and Wire MoM, time-domain TLM method and FDTD method.

The second problem, that is, a thin wire in an enclosure with and without the presence of passengers, is simulated by TLM method and presented in Section 3.

The reasons for the choice of these two models are the following: in vehicles, extensive use is made of long communication and control cables spanning the entire length of the vehicle. These cables are placed very near the roof or floor of the vehicle (effectively a ground plane). It is important to establish the level of coupling between these long cables and mobile devices used by passengers. The choice of the first problem is therefore dictated by this configuration – a long cable near ground subject to interference from a short dipole representing the mobile device. The second problem studied is similar but also takes into account, as far as possible, the actual environment in a vehicle (i.e. walls, windows and passengers). These two problems allow a reasonable assessment of coupling effects to be made. The overall aim is to establish the general level of coupling for a range of problem parameters (cable length, height, mobile position and polarisation relating to cable and so on).

2 Thin wire above a ground plane in an open area

The EM coupling between a half-wave dipole antenna and a thin wire in the near field is simulated with different numerical methods, such as TLM [7], MoM/NEC [8], MoM/CONCEPT [9] and Wire MoM [10]. A selection of simulation results is presented here and compared with experimental results.

2.1 Configurations and parameters in the simulation models

The configurations investigated are schematically shown in Fig. 1. As mentioned earlier, this is a configuration dictated by practical cable and coupling arrangements inside vehicles. We have chosen this realistic configuration as opposed to a canonical configuration to establish practical coupling limits. The dimensions of the ground plane are 12 m long and 3 m wide. A thin wire with varied lengths, typically 1, 5 and 10 m, and with different heights above the ground plane, such as 5, 30 and 80 cm, is simulated. The thin wire, of 2-mm diameter, is parallel to the ground plane with one end open and the other end with a 150 Ω load, of which 50 Ω represents the input impedance of the measuring receiver. The termination point of 150 Ω is at 1 m distance from the edge of the ground plane, and centred in the perpendicular direction, that is parallel to the y-axis above the ground plane (the ground plane and termination point in different research centres varied slightly). The antenna is modelled as a half-wavelength dipole tuned to 900 MHz frequency and excited by a 50 Ω, 1 V source.

The dipole is operated in three different polarisations, that is, horizontal polarisation, parallel to the x-axis; perpendicular polarisation, parallel to the y-axis; and vertical polarisation, parallel to the z-axis, shown schematically in Fig. 1. The positions of the dipole in the y-axis and the z-axis directions of the simulation configuration are fixed in a way that the nearest point of the dipole is 10 cm above the wire and 10 cm backwards as illustrated in Fig. 1.

Simulation results for maximum current distribution along the thin wire for three dipole polarisations are presented in Fig. 2. Simulation results for the voltage across 50 Ω, representing the input impedance of the measuring receiver, for three dipole polarisations and for 1 and 10-m long wires, are presented in Figs. 3 and 4, respectively. Simulation results for the voltage across 50 Ω, for the horizontal polarisation and for three different thin wire heights above the ground plane for a 1 m long thin

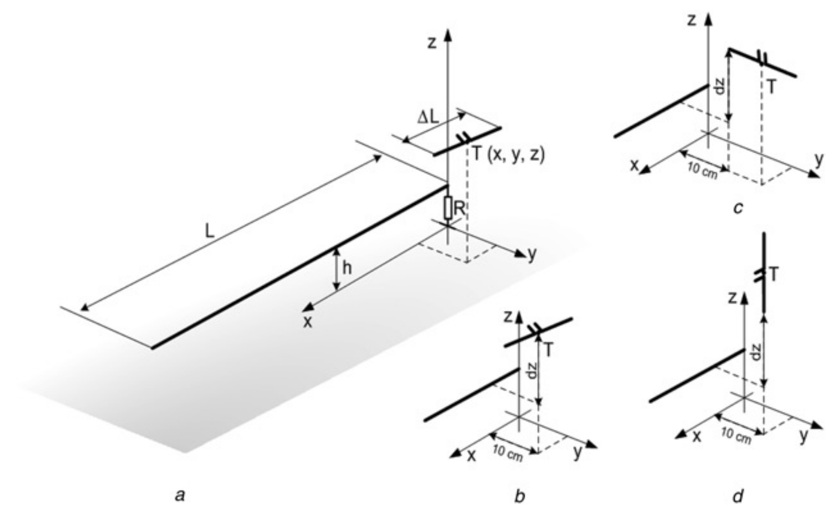

Fig. 1 *Schematic illustration of a thin wire above a ground plane, together with a dipole in three polarisations*

a Simulation configuration

b–d Three dipole polarisations, that is, horizontal polarisation, parallel to the x-axis; perpendicular polarisation, parallel to the y-axis; and vertical polarisation, parallel to the z-axis, respectively

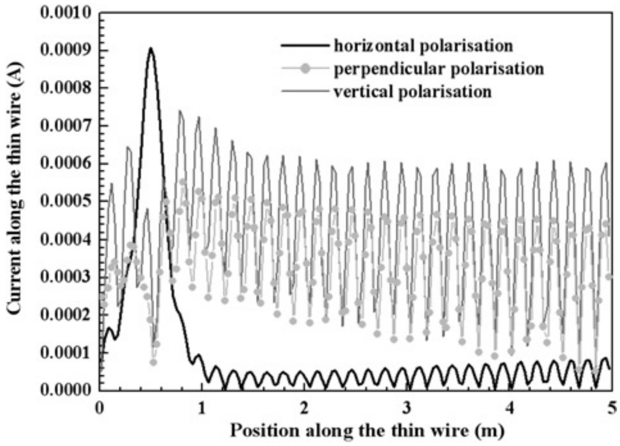

Fig. 2 *Current along the thin wire of 5 m long and 5 cm above the ground plane, excited by a dipole with three polarisations, that is, horizontal, perpendicular and vertical polarisations, respectively*

wire, are presented in Fig. 5. Comparison between various simulations and experiments is presented in Section 2.4.

2.2 Comparison of currents along the thin wire excited by different dipole polarisations

A thin wire of 5 m long and 5 cm high above the ground plane is excited by a dipole with three polarisations, that is, horizontal, perpendicular and vertical polarisations. The dipole is at the calibration point, that is, with the nearest dipole-tip at 0.5 m to the wire junction. This configuration has been simulated by different groups with different numerical methods, such as the MoM-based NEC, CONCEPT, Wire MoM and TLM. Simulation results obtained by the above methods are in good agreement with each other. Fig. 2 shows the simulation results obtained by the MoM/NEC method.

Similar simulations for a variety of configurations, such as, a thin wire of 1, 5 and 10 m long, with its height above the ground plane of 5, 30 and 80 cm, respectively, have also been carried out. These results show that there

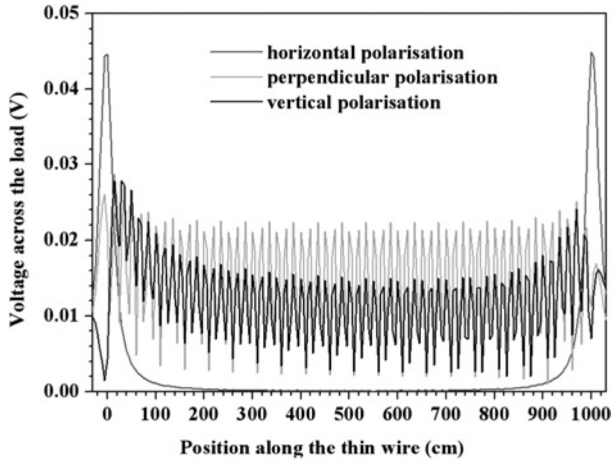

Fig. 4 *Voltage across the 50 Ω load as a function of the dipole position along the thin wire for three dipole polarisations*

Thin wire is of 10 m long and 5 cm above the ground plane, excited by a dipole with three polarisations, that is horizontal, vertical and perpendicular, respectively

is a small effect on the total current along the thin wire when the length or height of the thin wire is varied.

2.3 Comparison of load voltages excited by different dipole polarisations and for different heights of the thin wire above the ground plane

The voltage across the 50-Ω load, representing the input impedance of the measuring receiver, is simulated as a function of the dipole position along the thin wire for the cases that the thin wire is excited by three dipole polarisations. The dipole is moved along the thin wire from $x = -30$ cm up to the wire length $+30$ cm. In this way, the dipole may operate along the full length of the thin wire, and starting/ending at 1 wavelength away from the wire ending points. This problem has been simulated by different numerical methods, such as MoM-based NEC, CONCEPT, Wire MoM, TLM and FDTD, with good agreement with each other.

Figs. 3 and 4 present the simulation results obtained by the MoM-based NEC method. The thin wire is 1 and 10 m long, respectively, and 5 cm high above the ground plane.

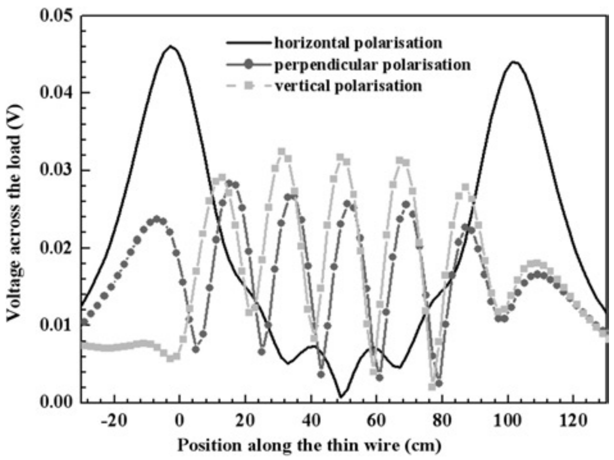

Fig. 3 *Voltage across the 50 Ω load as a function of the dipole position along the thin wire for three dipole polarisations*

Thin wire is of 1 m long and 5 cm above the ground plane, excited by a dipole with three polarisations, that is, horizontal, vertical and perpendicular, respectively

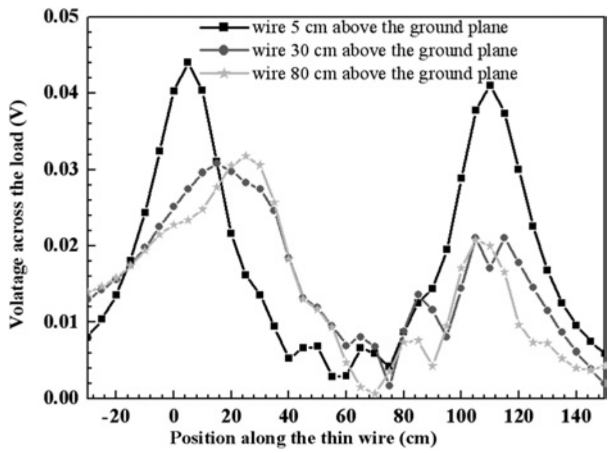

Fig. 5 *Voltage across the 50 Ω load as a function of the dipole position along the thin wire*

Thin wire is of 1 m long and 5, 30 and 80 cm above the ground plane, excited by a dipole with horizontal polarisation, that is, parallel to the x-axis

The dipole with horizontal polarisation, that is, parallel to the x-axis, gives two very apparent maximum peaks when it is placed near the wire ends and minimum value when the dipole is placed in the middle of the thin wire. Meanwhile, the dipole with perpendicular polarisation, that is, parallel to the y-axis, or vertical polarisation, that is, parallel to the z-axis gives quite a few local maximum peaks when it is moved along the thin wire.

Similar simulations have been carried out for a thin wire with varied length and different height above the ground plane, excited by different dipole polarisations. Fig. 5 shows the simulation results of the load voltage as a function of the dipole position along the thin wire for the cases that the thin wire is 1 m long and 5, 30 and 80 cm height above the ground plane, respectively, and the dipole is in the horizontal polarisation.

The results obtained by different simulations performed using different techniques and in different research centres are consistent, thus giving confidence in the simulation process. Although the detailed responses vary depending on the general configuration used, general conclusions may be drawn as to the general level of coupling. We see from the figures presented here and more investigations not shown that for a 1 V mobile device, the peak voltage coupled to a cable is typically in the range of 25–50 mV. In our experiments, the radiated power is 7 dBm. A standard GSM phone with 2 W maximum output power (33 dBm) radiates a higher power by 26 dBm. Hence, assuming the same antenna coupling, the induced peak voltage for a standard phone will be higher by a factor of 20. This conclusion holds for a different cable length, cable height and mobile device polarisation (see Figs. 3–5). Similarly, the peak current along the cable does not exceed 1 mA. The value of this work is in demonstrating that estimates of maximum coupling can be made from a small number of simulations without the need to cover the entire parameters space.

2.4 Comparison of simulation results with experimental results

The simulation results shown below are obtained by different groups using different numerical methods. The University of Split uses MoM/NEC method. The Wroclaw University of Technology uses the MoM/NEC method. The Leibniz University of Hannover uses the MoM/CONCEPT method. The Swiss Federal Institute of Technology uses the MoM/NEC method. The SP Technical Research Institute of Sweden uses Wire MoM method. The Seibersdorf campus of ARC uses Wire MoM method. Meanwhile, experimental measurements have been conducted by the University of Split, the University of Liège and the Seibersdorf campus of ARC. It can be observed that the simulation results from different research groups are largely in good agreement with each other, whereas the experimental results conducted in the Austrian Research Centers, campus Seibersdorf fit better with the simulation results than the others. A ferrite loaded cable and a precision reference dipole with a balun, which has excellent symmetry (balun balance is specified better than $\pm 2^{\circ}$ in phase and ± 0.2 dB in amplitude), have been used in the Seibersdorf experiments, which ensure that there is no current on the shielding of the feed cable and the feed cable does not act as part of the dipole antenna. The experimental results obtained at Seibersdorf were normalised at 1 V across the antenna, whereas other simulation and experimental results were obtained for 1 V (emf) from a 50 Ω source which was equal to 0.6 V nominal voltage across the antenna impedance. The Seibersdorf measurement results reflected 13 dBm dipole input power, because all correction factors (balun, cable, mismatch and so on) were already considered. Hence, as expected, the Seibersdorf experimental results were $\sim$4.5 dB higher. We thus rescaled the Seibersdorf experimental results by a factor of 0.6 (-4.5 dB) in the Figs. 6–8. As a result, the Seibersdorf experimental results are in excellent agreement with simulation results. We observed that some of the differences in simulated results were because of the use of different discretisation, and similarly the difference between experiments results could be attributed to different laboratory environments and location of feed cables, and to the use of a monopole rather than a dipole in the case of experiments at Liège.

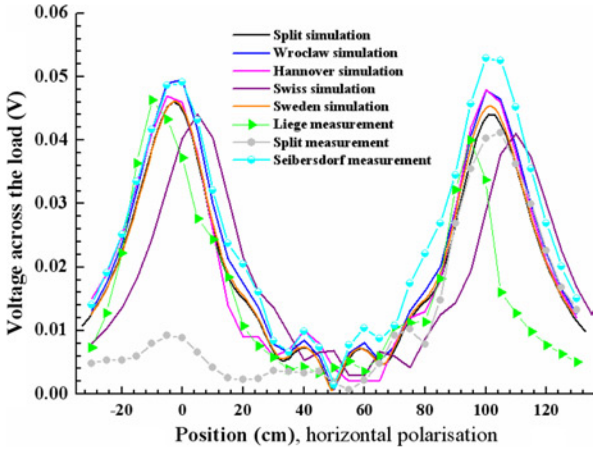

Fig. 6 *Comparison of the simulation and experimental results of the voltage across the load*

Thin wire is 1 m long and 5 cm above the ground plane. Dipole is in horizontal polarisation, that is, parallel to the x-axis

Fig. 6 shows a comparison between experiments and simulations for the horizontal dipole polarisation. Simulation results are in good agreement, and the Seibersdorf experimental result is in excellent agreement with simulation results. However, some experimental results are lower and asymmetric. We attribute these differences to proximity effects between the cable to the receiver and the long wire. It was difficult to reproduce exactly in each site the experimental arrangements (cable disposition, spaces and supports) and this accounts for some of the observed differences. In addition, the cabling used for measurements was not included in the numerical models. Illustrative details of the experimental set-up are shown in the Appendix.

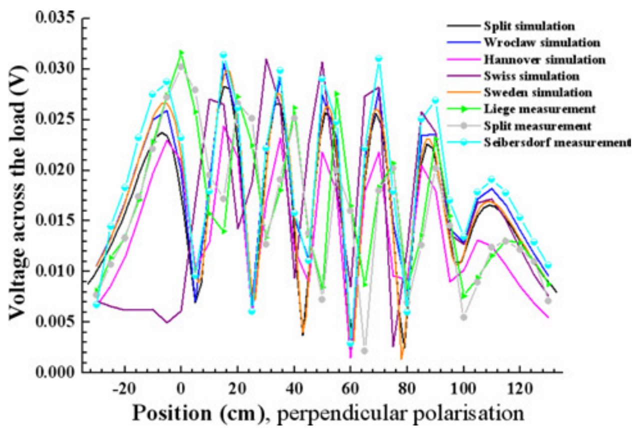

Fig. 7 *Comparison of the simulation and experimental results of the voltage across the load*

Thin wire is 1 m long and 5 cm above the ground plane. Dipole is in perpendicular polarisation, that is, parallel to the y-axis

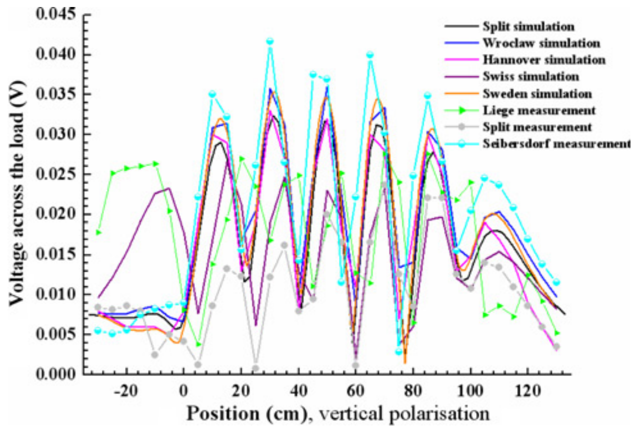

Fig. 8 *Comparison of the simulation and experimental results of the voltage across the load*

Thin wire is 1 m long and 5 cm above the ground plane. Dipole is in vertical polarisation, that is, parallel to the *z*-axis

Fig. 7 is similar to Fig. 6, but for the perpendicular dipole polarisation.

The shifts observed in the experiment results are because of particular measurement arrangements (e.g. the use of spacers, location of cables and so on), which are difficult to capture in simulations.

Results for vertical dipole polarisation are shown in Fig. 8, with a good level of agreement. Similar comments apply in relation to shifts as for Fig. 7.

Simulation results were also obtained at Seibersdorf for Figs. 6–8, which are practically identical to these from Wroclaw.

3 EM coupling between mobile wireless devices and wiring systems inside a vehicle

A full-field rigorous TLM solver, developed by the University of Nottingham, is used to simulate the EM coupling of a mobile wireless device to a wiring system inside a vehicle with or without the presence of passengers. Such coupling problems present a formidable modelling task because of the co-existence in the same problem of electrically large (e.g. the frame of a large vehicle) and small (e.g. wires, mobile antennas) objects. The focus of the following simulations is to present techniques, which allow such models to be constructed leading to efficient computation, and to show typical results.

3.1 Simulation configuration

The vehicle is 6-m long, 3-m wide and 2-m high, with eight windows. One is in the front, one is in the back and three are on each side in the longitudinal direction. The front and back windows are 2.33-m wide and 1.667-m high. The windows on both sides in the longitudinal direction are 1.5-m wide and 1.33-m high. The directions of the *x*-, *y*- and *z*-axes are horizontal, vertical and perpendicular, respectively, with the origin in the right hand near corner.

A thin wire, 5-m long, of 2-mm diameter, is parallel to, and 5-cm from the top plane of the vehicle. It is open at one end and terminated by a load of 150 Ω at the other to the top plane. The wire junction is 1 m from the back plane on the origin side. A passenger with a mobile is sitting underneath the thin wire, with the mobile antenna vertical to the thin wire. The centre of the dipole is 18 cm directly below the thin wire junction end. A simplified model of a passenger is placed centrally above the bottom plane of the vehicle in the *z*-direction, facing the front in the *x*-direction. The mobile phone is 5 cm away from the head. The cross section of the simulation model in the *z*-direction and *x*-direction is schematically shown in Figs. 9 and 10, respectively. In the case of the presence of four passengers inside a vehicle, these passengers are in front of each other in the horizontal direction with 50 cm space among them. Material with electrical properties resembling human tissue is selected by setting the dielectric material properties of the tissue as $\varepsilon_r' = 56$, $\sigma_e = 1$ S/m. This is typical of biological tissues at 900 MHz.

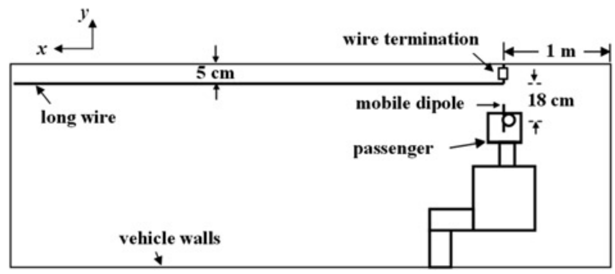

Fig. 9 *Cross section of the simulation model in the z-direction*

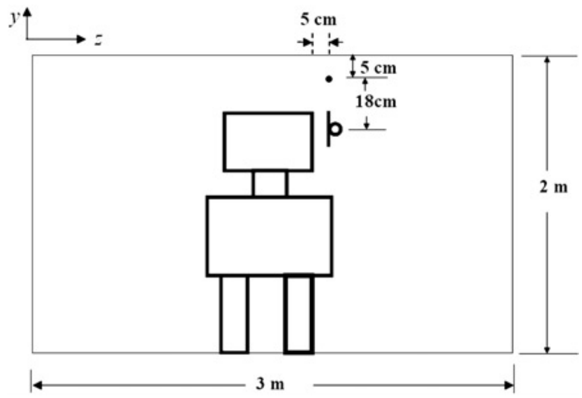

Fig. 10 *Cross section of the simulation model in the x-direction*

3.2 Simulation model

A canonical system consisting of a mobile phone and a typical long wire interconnection inside a vehicle is simulated for the EM coupling between a half-wave mobile dipole antenna and a thin wire in the near field using the TLM method, with and without passengers inside the vehicle (shown in Figs. 9 and 10). The mobile antenna is a half wave dipole antenna with an impedance of 50 Ω and a voltage of 1 V. It is excited either with a sinusoidal wave having a frequency of 900 MHz, or by a Gaussian pulse with a half width of 0.556 ns. For the TLM simulation results presented in this paper, the mesh size is chosen as 1.6667 cm. In order to model thin wires using this mesh, we have employed special thin-wire formulae, which are described in more details elsewhere [11].

3.3 Simulation results

For the cases with and without passengers inside a vehicle, EM coupling of a mobile to a long thin wire is simulated by exciting a sinusoidal or a Gaussian source. In the case of a 900 MHz sinusoidal dipole, the EM coupling of the dipole antenna to the thin wire is monitored for its maximum coupling current along the thin wire; the magnetic field in the x–y plane with the dipole and the thin wire; the feed

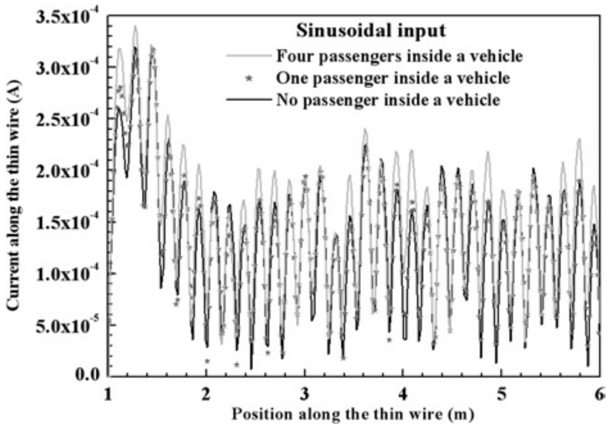

Fig. 11 *Comparison of the maximum currents along the thin wire excited by a sinusoidal dipole, for the cases without passenger, with one passenger and with four passengers inside a vehicle*

voltage at the dipole feed point; and the voltage across the load with an resistance of 50 Ω. In the case of the Gaussian source, fast fourier transform (FFT) analyses of the voltages across the load and at the dipole feed point are carried out. The ratios of the FFT voltage across the load, to the FFT voltage at the dipole feed point as a function of frequency, are plotted for the above cases.

The maximum currents along the thin wire for the cases with and without passengers inside a vehicle are shown and compared in Fig. 11. We note that the presence of passengers has a small effect on the coupling as the Q-factor of the cavity is determined essentially from the large apertures (windows).

The ratios of the FFT voltage across the load, to the FFT voltage at the dipole feed point as a function of frequency for the cases with and without passengers inside a vehicle, are compared and shown in Fig. 12.

It can be seen from Figs. 11 and 12 that the presence of passengers inside a vehicle has a small impact on the level of the EM coupling of a mobile phone to a typical long thin wire inside a vehicle. The simulation results of the EM couplings of a mobile phone to a typical long thin wire inside a vehicle obtained by the sinusoidal and Gaussian excitations at the mobile phone operating frequency 900 MHz are very similar. Owing to relatively low-damping, very long run-time is required in the simulations in order to achieve convergence. We therefore anticipate that the curves in Fig. 12 will change somewhat as a result of an extension of the simulation time. In addition, location of the mobile phone closer to the head will have a greater impact on the results.

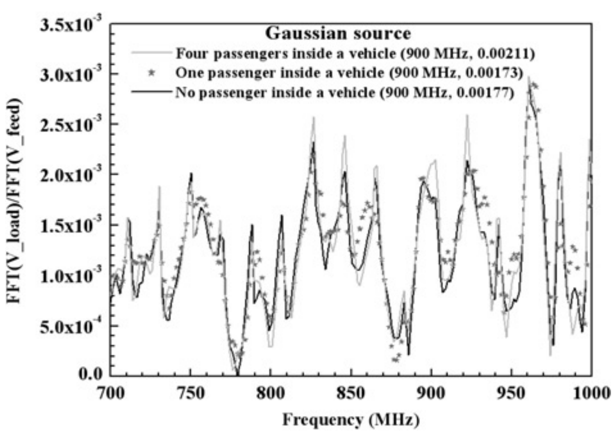

Fig. 12 *Comparison of the maximum currents along the thin wire excited by a Gaussian source, for the cases without passenger, with one passenger and with four passengers inside a vehicle*

4 Conclusions

Generic problems of near-field radiating antenna coupling into a cabling system have been addressed and analysed for various dipole to wire configurations, in an open area or inside an enclosure. Different simulation methods, including MoM/NEC, MoM/CONCEPT, Wire MoM and TLM, have been implemented and used for simulations. Simulation results obtained by different institutes with different methods have been compared and satisfactory agreement was observed. Simulation results were also compared with experimental results, showing satisfactory agreement. Simulation results show that variations in the dipole polarisation, wire length and wire height have limited impact on the maximum value of the induced load voltage. The presence of passengers inside a vehicle has a small effect on the magnetic field distributions and hence the wire coupling inside the vehicle provided substantial damping is caused by losses through windows. The studies reported here confirm that a small number of simulations can give a reasonable assessment of the strength of coupling for a wide range of configurations.

The promising conclusion from this work is that simulations done using different techniques and in different research centres are in good agreement, thus giving confidence to the models used. Comparison with analytical results were not possible as no analytical solutions are available for problems of this complexity. The intention of this work was to address practical problems. Each numerical method used has been validated before against analytical results for canonical problems, so this work was not repeated here. Similarly, the intention was not to compare different techniques for efficiency as broadly speaking the advantages and disadvantages of each technique are known. Techniques based on the MoM applied in the frequency domain are very efficient for wire-like problems, such as the first configuration studied here. Finite techniques based on differential equation time-domain formulations such as FDTD or TLM are more effective when applied to problems with cavities and non-uniformities such as the second problem examined here.

5 Acknowledgments

We are glad to recognise the help and assistance of the European Action COST 286 Team throughout the investigations under this Joint Technical Action.

This work was done with support and on behalf of the European Action COST 286 (EMC in Diffused Communications Systems).

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7 Appendix

7.1 Typical experimental set-up

As an illustration of the experimental parameters, we give some details of the setup used at Seibersdorf: Anechoic chamber (usable volume $6.6 \times 3 \times 3\ m^3$, absorbers VHP 26 and 36, usable to 40 GHz); Ground plane (Al, $1.5 \times 4.3\ m^2$); Wire (brass, 2-mm diameter); reference point (1.65 m from the edge of ground plane with resistor centre 17 mm above ground plane and resistor length 5 mm). Measurement equipment: signal generator (Rohde & Schwarz SMT 03); EMI receiver (Rohde & Schwarz ESIB 26); precision reference dipole tuned for 900 MHz, 15.5-cm length; Balun attenuation 10.6 dB; dipole connected to a ferrite loaded cable; measurement cables with altogether 13 dB attenuation.