Intra-train Wagon Wireless Channel Connectivity Analysis of Ultra Dense Node Deployments

Imanol Picallo[1], Hicham Klaina[2], Peio López-Iturri[1], Jose Javier Astrain[3], Mikel Celaya-Echarri[4], Leyre Azpilicueta[4], Ana Alejos[2], Asier Perallos[5], Agusti Solanas[6], and Francisco Falcone[1(✉)]

[1] Department of Electrical, Electronic and Communication Engineering, UPNA, Pamplona, Spain
{imanol.picallo,peio.lopez, francisco.falcone}@unavarra.es

[2] Signal Theory Department, University of Vigo, Vigo, Spain
analejos@uvigo.es

[3] School of Engineering and Sciences, Tecnologico de Monterrey, Monterrey, Mexico
josej.astrain@unavarra.es

[4] Department of Statistics, Informatics and Mathematics, UPNA, Pamplona, Spain
leyre.azpilicueta@tec.mx

[5] Engineering Faculty, University of Deusto, Bilbao, Spain
perallos@deusto.es

[6] Department of Computer Engineering and Mathematics, Universitat Rovira i Virgili, Tarragona, Spain
agusti.solanas@urv.cat

Abstract. The advent of Internet of Things will provide massive connectivity and seamless interaction, mainly enabled by wireless communication systems. In this work, intra-wagon connectivity will be analyzed in terms of different system wireless system requirements. The specific application considers the use of standards such as 802.11 ah, Bluetooth Low Energy and Frequency Range 1 5G new radio spectrum, with the aid of in-house deterministic 3D Ray Launching algorithm, providing precise characterization of multiple parameters, such as interference distribution, received power levels and time domain characteristics.

Keywords: Intra-wagon communications · 802.11 ah · BLE · 5G NR · 3D Ray Launching

1 Introduction

The progressive adoption of Smart City and Smart Region paradigms is leading towards context aware environments, in which high levels of user interaction are one of the main characteristics. In this sense, wireless communication systems play a key role

H. Jin et al. (Eds.): CROWNCOM 2021/WiCON 2021, LNICST 427, pp. 269–279, 2022.
https://doi.org/10.1007/978-3-030-98002-3_20

in order to enable seamless interaction in multiple user/environment conditions. In this sense, given the advent of Internet of Things (IoT), highly variable and dynamic channel conditions can be established, in which scenarios of high complexity and large node densities are commonplace. In order to comply with quality of service and quality of experience requirements, interoperation between multiple wireless systems is envisaged, providing optimal coverage/capacity relations in the scenarios under test [1–5]. In this way, depending on node density, coverage area and transmission rate, different systems within the range of personal area communications, wireless sensor networks, wireless local area networks or public land mobile networks can be employed. In the case of IoT related applications, there are additional considerations to take into account, such as reduced form factor, low cost, high node density and limited energy availability. With this in mind, systems such as 802.11ah, Bluetooth Low Energy (BLE) or 5G New Radio operating in Frequency Range 1 (i.e., below 6 GHz) are some of the candidates under consideration in order to enable IoT oriented wireless connectivity.

In the context of train communications, the implementation of context aware user interactive environments is a goal related with the adoption of Intelligent Transportation System paradigms. By embedding dynamic communication systems within different elements of the train system infrastructure, different types of services can be provided, such as telecontrol and telemetry, passenger assistance, location/user-oriented marketing or multi-modal transportation handling, among others. Wireless systems play a key role in terms of providing interconnectivity within rail transportation systems [6, 7]. Among these, intra-wagon connectivity enables the development of different applications, given by different requirements by passengers as well as by train operators. These scenario pose specific challenges in terms of wireless system operation, owing to high transceiver density, the presence of users and interaction with human body in terms of blockage/dispersion and large scatterer density leading to strong multipath components, inherent to the underlying metallic structure within the wagon. Therefore, precise wireless channel characterization is compulsory in order to provide optimal device/network design in terms of coverage/capacity relations, particularly in the case of high node density conditions. In this sense, deterministic channel propagation methods can provide accurate results in order to extract information such as interference distribution or hot-spot identification, among others.

In this work, wireless channel characterization for intra-wagon train communications is performed, considering multiple wireless communication systems providing services for IoT enables applications, such as 802.11ah, BLE and 5G NR FR1 systems. Deterministic wireless channel estimation for the complete scenario volume, for frequency domain as well as time domain parameters is obtained, as a function of transceiver node location in the scenario under test.

2 Intra-wagon Wireless Channel Characterization

In order to perform the intra-wagon wireless channel characterization, an in-house implemented 3D Ray Launching code has been employed. the algorithm has been coded in Matlab and different modules have been added in order to reduce computational cost and increase simulation accuracy, including hybrid neural network interpolators, bi-dimensional electromagnetic diffusion equation or deep learning data base extraction based on collaborative filtering [8, 9]. A realistic simulation scenario has been implemented in order to consider all the effects of the surrounding environment, given by scatterer location (i.e., seats, intra-wagon cabinets and railings) and dispersive material properties. A schematic representation is depicted in Fig. 1.

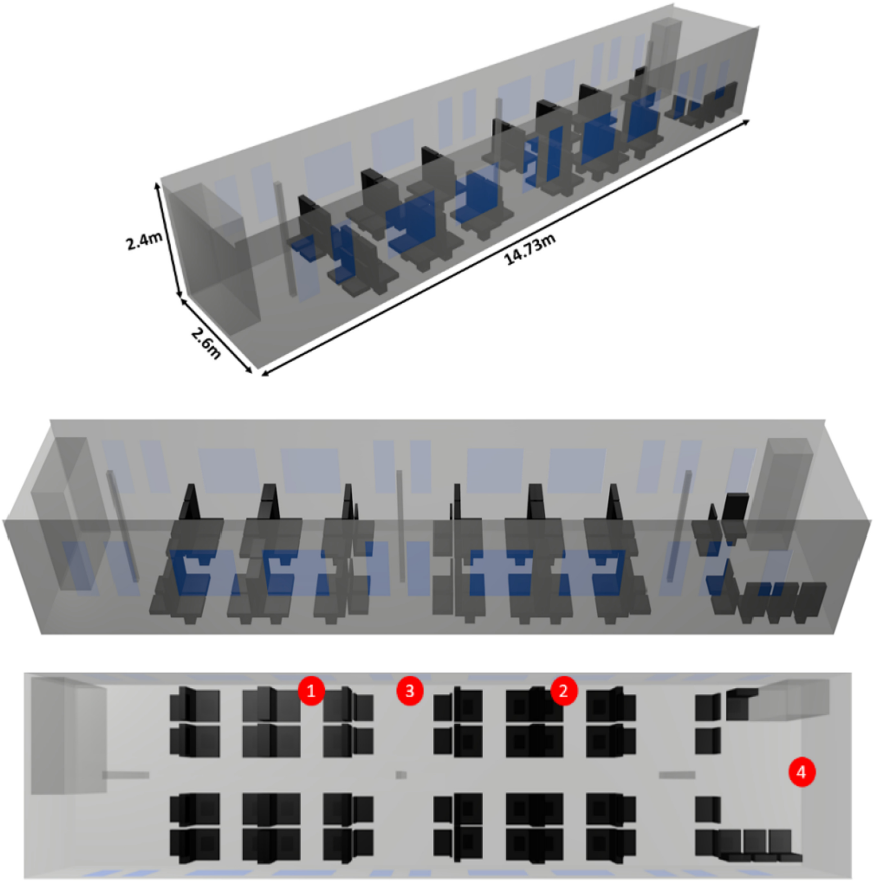

Fig. 1. Schematic of the intra-wagon scenario and the location of the embedded transceivers.

Simulation parameters have been set according to extensive convergence analysis, in order to optimize simulation time whilst maintaining high accuracy values (i.e., maximum number of reflections until extinction of launched ray, angle resolution in the polar plane, angular resolution in the azimuthal plane and cuboid mesh cell dimensions) [10]. The simulation parameters employed are detailed in Table 1 and the frequency dispersive material characteristics (which in this specific study remain practically constant for all the frequencies under analysis) are given in Table 2.

Table 1. 3D-RL simulation parameters.

Parameters	Values
Operation frequency	868 MHz (802.11ah-Europe), 2.4 GHz BLE, 3.5 GHz 5G NR FR1
Transmitted power	10 dBm
Antenna type	Monopole
Antenna gain	0 dBi
Launched rays angular resolution	1°
Maximum number of rebounds	6
Cuboids size (Mesh resolution)	10 cm × 10 cm × 10 cm
Difraction phenomenon	Activated

Table 2. 3D-RL material properties.

Material	Relative permittivity (ε_r)	Conductivity (σ) [S/m]
Air	1	0
Metal (aluminium)	4.5	37.8×10^6
Polypropylene	3	0.11

Received power levels as a function of the embedded transmitting node have been obtained for the complete volume of the train wagon, enabling coverage analysis considering potential location of receivers as well as the wireless system employed. Figure 2 depicts the estimation of bi-dimensional distributions of received power levels, considering embedded node 1 as the transmitting node, for a cut-plane height of 1.5 m, for 802.11ah, BLE and 5G NR1. It's worth noting that there are two locations in the plots (far left-hand side and upper right-hand side) there is deep signal fading, given by the existence of both metallic cabinets within the wagon.

As a function of operating frequency as well as by the distribution of scatterers within the scenario, power distributions vary accordingly. This effect can be clearly seen by considering different cut-plane heights, which are depicted in Fig. 3 (considering as an example the case of 802.11 ah), as well as by considering different embedded antenna locations, depicted in Fig. 4 (for the case of BLE) and depicted in Fig. 5 (considering as an example the case of 5G NR FR1). Despite the fact that the scenario under test has a limited volume size, the impact of interior furnishings (mainly seats, with a large density of highly reflective scatterers) can be clearly observed as potential location of receiver nodes is varied, as well as the vicinity of each one of the transmitting nodes considered.

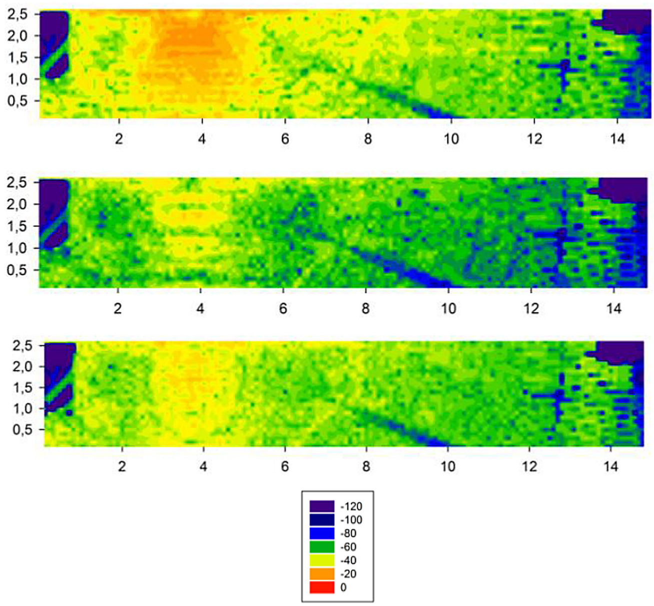

Fig. 2. Estimation of received power levels considering TX Antena 1 at a cut-plane height of 1.5 m, for 802.11 ah (top), BLE (middle) and 5G NR FR1 (bottom).

An example is given in the top 2 images in Fig. 4, which correspond to cut-plane height of 0.5 m and 1 m, respectively. Shadowing effects can be observed following a longitudinal distribution, approximately every 2 m. This is caused by the presence of the seats, with predominant non-line of sight links at those considered heights. Similar considerations can be seen for open space regions within the indoor train wagon cabin or the existence of elements such as cabinets, in which received power levels decrease considerably (specially in the case of considering metallic doors, which is the usual case within the indoor train environment). This effect can also be observed in Fig. 3 and Fig. 4, in the upper left hand of the received power level plots, corresponding to the presence of an operation cabinet within the train wagon, with losses in the excess of 20 dB owing to the presence of the metallic doors which enclose the cabinet volume.

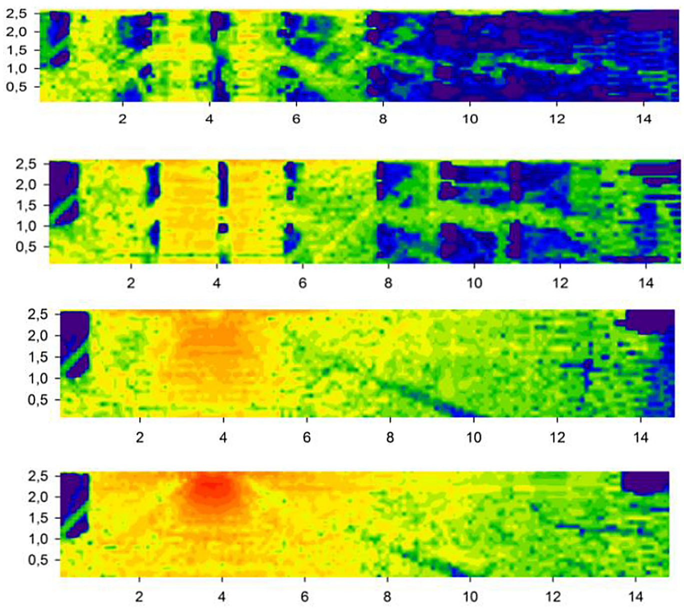

Fig. 3. Estimation of received power levels considering Antena -802.11ah and variations of cut plane height (from top to bottom) of 0.5 m, 1 m, 1.5 m and 2 m, respectively

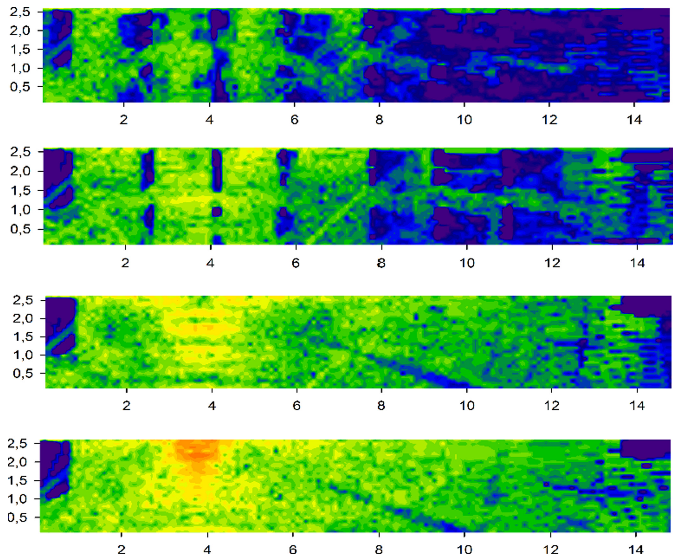

Fig. 4. Estimation of received power levels considering Antena 1-BLE and variations of cut plane height (from top to bottom) of 0.5 m, 1 m, 1.5 m and 2 m, respectively

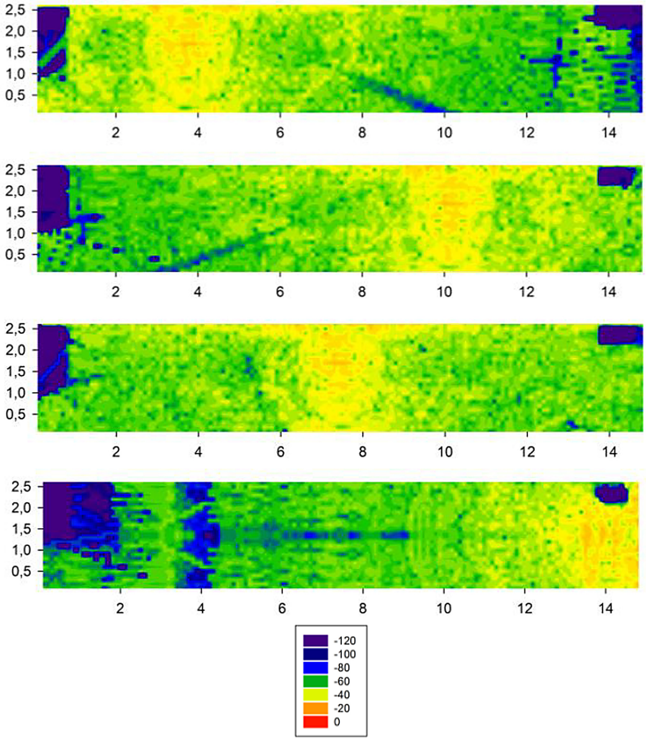

Fig. 5. Estimation of received power levels considering 5G NR FR1 at a cut plane height of 1.5 m for (top to bottom figures), node A1, A2, A3 and A4, respectively

Based on the estimation of received power levels, coverage/capacity relations can be obtained as a function of receiver sensitivity, which can be quantitatively evaluated by obtaining linear radial received power level distributions, such as the ones depicted in Fig. 6, for the case of 802.11 ah and in Fig. 7, for the case of BLE. The impact of height modification is clearly visible within this scenario, in which the location of seats leads mainly to non- line of sight conditions, as well as the impact of multipath propagation components, which build up with distance as interaction with scatterers increases. It is worth noting that estimations can be obtained within the complete intra-train wagon scenario, enabling to consider the location of transceivers at any given point within the wagon.

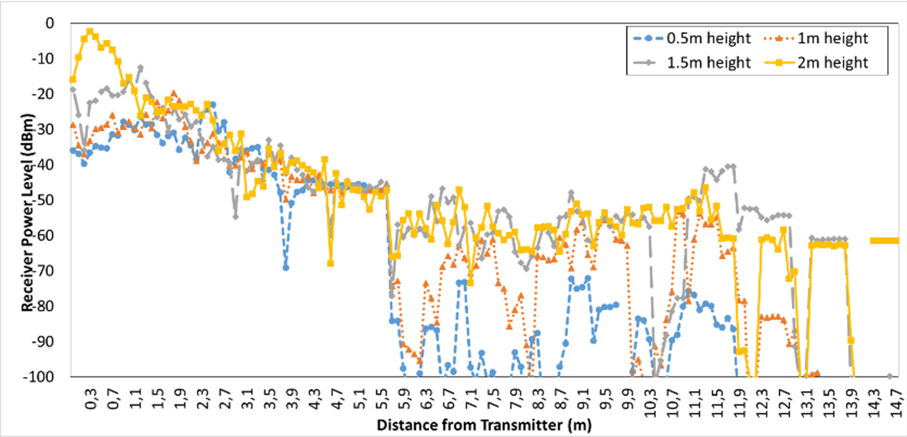

Fig. 6. Estimation of received power levels for linear radials, considering embedded transceiver A4 and cut plane heights of 0.5 m, 1 m, 1.5 m and 2 m, for the case of 802.11ah

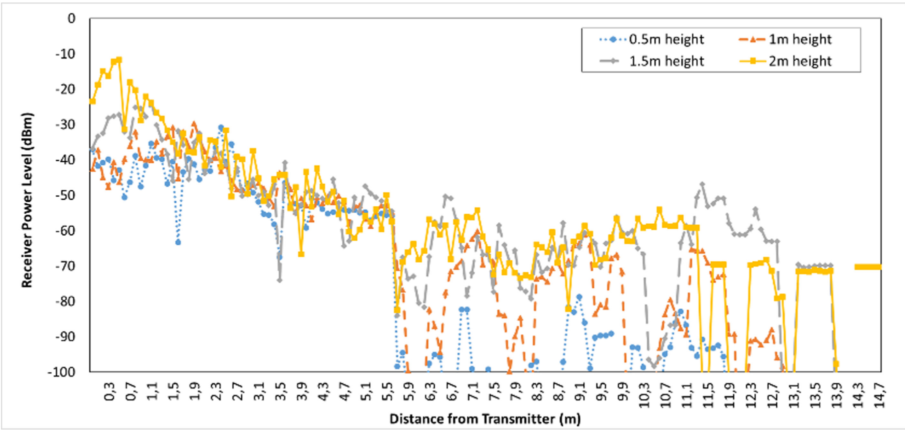

Fig. 7. Estimation of received power levels for linear radials, considering embedded transceiver A4 and cut plane heights of 0.5 m, 1 m, 1.5 m and 2 m, for the case of BLE

Multipath propagation characteristics can also be analyzed as a function of time domain parameters, such as power delay profiles or delay spread estimations, which can subsequently be employed to analyze elements such as coherence time or time of flight. Time domain characteristics can be extracted from the complete volume of the scenario under analysis. Examples of results for power delay profile estimations are depicted in Fig. 8 (for 802.11 ah) and Fig. 9 (for BLE), considering in both cases location of transceiver A1 and A4.

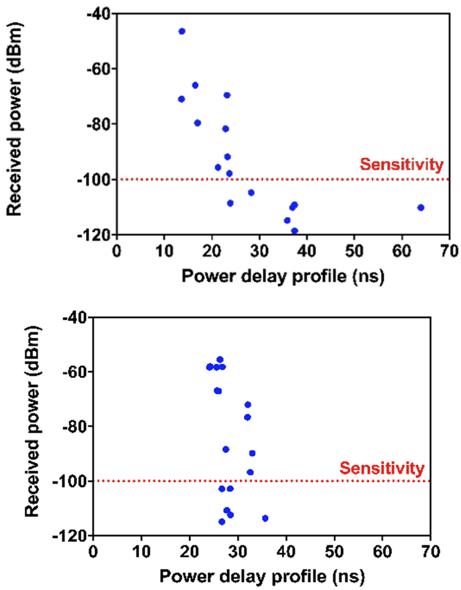

Fig. 8. Power delay profile estimations, considering 802.11 ah, for the case of location A1 (top figure) and A4 (bottom figure)

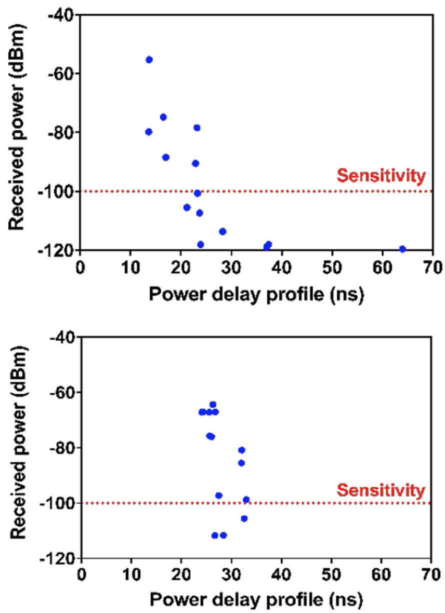

Fig. 9. Power delay profile estimations, considering BLE, for the case of location A1 (top figure) and A4 (bottom figure)

The results depicted for the PDP show the relevance of multipath propagation within the intra-wagon train environment. In the case of the results obtained for 802.11ah, location A1 presents field components that span in the 10 ns–70 ns range, whereas in the case of location A4, the components span in a much narrower time range, from 25 ns–35 ns. These results indicate that delay spread is strongly variable within the intra-wagon environment, which has a direct impact on channel equalization considerations within transceiver design.

Delay spread estimations have also been obtained, for the complete intra-wagon train scenario. Results are depicted in Fig. 10, considering different cut plane heights, for BLE, in which the effect of multipath propagation can be once again clearly observed, as a function of differences in received time components, owing to the effect of the large number of scatterers within the scenario. The differences are particularly visible when going from 1 m to 1.5 m height cut planes. This is once again given by the effect of the presence of the rows of seats within the scenario, which lead to non-line of sight links mainly for heights below 1 m.

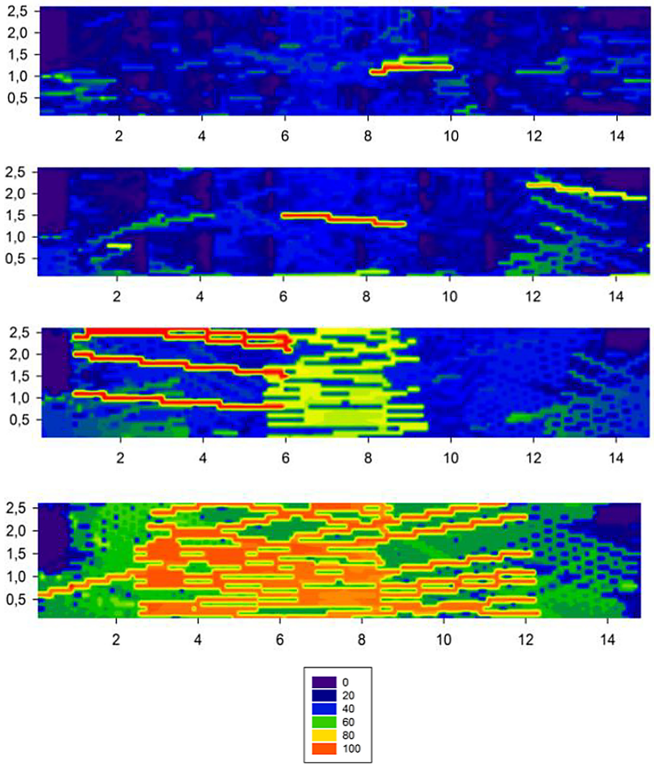

Fig. 10. Delay spread estimation (measured in ns), considering bi-dimensional cut planes at (top to bottom figure), for the case of node A3 BLE at cut plane heights of 0.5 m, 1 m, 1.5 m and 2 m

3 Conclusions

The integration of wireless communication systems in order to enable interactive passenger train applications plays a key role for the adoption of IoT within railway transportation systems. In this work, intra-wagon channel characterization for different systems (802.11 ah, BLE and 5G NR FR1) has been presented. With the aid of in-house deterministic ray launching code, the complete indoor intra-train wagon characteristics can be considered, such as furnishings (seats, handrails) or auxiliary elements (cabinets, doors). In this way estimations for the complete intra-wagon scenario have been obtained for frequency/power characteristics as well as for time domain characteristics, such as power delay profiles and delay spread distributions. The proposed methodology can be employed in order to perform coverage/capacity calculations which in turn aid in network/device design and planning process, enabling optimal network configuration. Future work involves the inclusion of human body models within the intra-wagon scenario, as well as the consideration of indoor/outdoor wireless link conditions.

References

1. Marcus, M.J.: Harmful interference and its role in spectrum policy. Proc. IEEE **102**(3), 265–269 (2014)
2. Ge, X., Huang, K., Wang, C.-X., Hong, X., Yang, X.: Capacity analysis of a multi-cell multi-antenna cooperative cellular network with co-channel interference. IEEE Trans. Wirel. Commun. **10**(10), 3298–3309 (2011)
3. Liu, F., Zhao, S.: Statistical resource allocation based on cognitive interference estimation in ultra-dense HetNets. IEEE Access **8**, 72548–72557 (2020)
4. Raza, A., Nawaz, S.J., Wyne, S., Ahmed, A., Awais Javed, M., Patwary, M.N.: Spatial modeling of interference in inter-vehicular communications for 3-D volumetric wireless networks. IEEE Access **8**, 108281–108299 (2020)
5. Karas, D.S., Boulogeorgos, A., Karagiannidis, G.K., Nallanathan, A.: Physical layer security in the presence of interference. IEEE Wirel. Commun. Lett. **6**(6), 802 (2017)
6. Tubaishat, M., Zhuang, P., Qi, Q., Shang, Y.: Wireless sensor networks in intelligent transportation systems. Wirel. Commun. Mobile Comput. **9**(3), 287–302 (2009)
7. Zhou, J., Chen, C.L.P., Chen, L., Zhao, W.: A user-customizable urban traffic information collection method based on wireless sensor networks. IEEE Trans. Intell. Transp. Syst. **14**(3), 1119–1128 (2013)
8. Azpilicueta, L., Falcone, F., Janaswamy, R.: Hybrid computational techniques for electromagnetic propagation analysis in complex indoor environments. IEEE Antennas Propag. Mag. **61**(6), 20–30 (2019)
9. Casino, F., Azpilicueta, L., López-Iturri, P., Aguirre, E., Falcone, F., Solanas, A.: Optimised wireless channel characterization in large complex environments by hybrid ray launching-collaborative filtering approach. IEEE Antennas Wirel. Propag. Lett. **16**, 780–783 (2017)
10. Azpilicueta, L., Rawat, M., Rawat, K., Ghannouchi, F., Falcone, F.: Convergence analysis in deterministic 3D ray launching radio channel estimation in complex environments. ACES J. **29**(4), 256–271 (2014)