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Analysis of Inter-Train Wireless Connectivity to Enable Context Aware Rail Applications

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Abstract. Train systems are fundamental players within multi-modal transit systems, providing efficient transportation means for passengers and goods. In the framework of Smart Cities and Smart Regions, providing context aware environments is compulsory in order to take full advantage of system integration, with updated information exchange among Intelligent Transportation system deployments. In this work, inter-train wireless system connectivity is analyzed with the aid of deterministic 3D wireless channel approximations, with the aim of obtaining estimations of frequency/power volumetric channel distributions, as well as time domain characteristics, for different frequency bands. The results show the impact of the complex inter-train scenario conditions, which require precise channel modelling in order to perform optimal network design, planning and optimization tasks.

Keywords: Inter-train communication, 3D Ray Launching Simulation, Wireless Communication Systems.

1 Introduction

Intelligent Transportation Systems are one of the main elements within the framework of Smart Cities and Smart Regions [1-3], with the aim of enabling secure, energy efficient and reduced contamination transportation of passengers and goods. Different transportation systems are considered and optimal use in general takes advantage of multi-modal use schemes. This is particularly relevant in the case of dense urban scenario, in which user travel can be enhanced by the combined use of different transportation systems, such as bicycles, shared cars, taxis, urban buses, trams, metro lines or trains, among others. In order to take full advantage of these different transportation means, information exchange combined with user preferences can be employed in order to implement adaptive route planning mechanisms. In this context, data collection and transmission is relevant in order to implement context aware environments that enable effective multi-modal transportation schemes. This is extensible to the case of train transportation, in which communication system integration is gaining increased interest [4-8].

Given inherent mobility requirements, wireless communication systems are mainly considered in order to enable the aforementioned data exchange. Different types of wireless communication systems can be employed, depending on the coverage/capacity requirements (i.e., required received power levels as a function of transceiver sensitivity thresholds, which at the same time, are given by transmission bit rate, modulation/coding schemes and electronic parameters, such as noise factor values), such as Low Power Wide Area Networks (LPWAN, such as LoRa/LoRaWAN), Public Land Mobile Networks (such as 4G/5G), Satellite Networks or Wireless Local Area Networks. Given the different operating conditions, such as transmission rates, coverage, number of nodes or cost, one of these systems or a combination of them can be employed. In general, currently the operation frequency is below 6 GHz, except for VSAT satellite communication systems or 5G NR Frequency Range 2 (initially in the 28 GHz frequency band), owing to larger coverage extension and lower system cost, as compared with higher frequency millimeter wave systems.

The selection of the corresponding wireless systems is strongly dependent on the frequency of operation, as this defines path loss (higher as frequency increases) and interference dependence (in principle higher as frequency ranges are lower, owing to spectrum congestion). Propagation losses are given by multiple factors, such as distance and interaction with the surrounding environment with multiple mechanisms, such as diffraction, diffuse scattering or multipath propagation, among others. Estimation of propagation losses can therefore be a complex task, especially for scenarios with large obstacle densities, which is the case of urban train environments.

In this work, wireless channel analysis for the case of inter-train communications is presented, with the aid of precise deterministic channel models. Different frequencies of operation are analyzed within the below 6 GHz. Time domain results are also presented, in order to gain insight on the impact of multi-path propagation within the train scenario under test.

2 Inter-Train Wireless Communication Scenario Analysis

In order to analyze coverage/capacity conditions within inter-wagon train wireless communication links, a deterministic geometric simulation approach has been employed. An in-house implemented 3D Ray Launching code has been used, based on the approximation of Geometric Optics with Uniform Theory of Diffraction, applied within the complete volume of the scenario under analysis. An arbitrary number of transmitter sources can be placed within any given location of the scenario. Once these sources (which are equivalent to active transmitters) have been defined, they launch rays with given volumetric angular resolution, as well as with specific reflection conditions (i.e., maximum number of reflections of any given ray until ray suffers power extinction). The volumetric representation of the scenario considers the shape, size and material characteristics (i.e., frequency dispersive dielectric constant and electric conductivity) of all the elements within the scenario. The code in implemented in Matlab and the parameters employed in terms of angular resolution, cuboid size and maximum number of reflections until ray extinction (given be previous convergence analysis studies [7-8]) are the following: angular resolution Δφ = Δθ = 1º, Δcuboid = 1m, N (maximum reflections enabled) = 6. A schematic representation of the scenario is depicted in fig. 1. The scenario is given by two trains located within the landing platform of an urban train station. Full details of the trains are provided, including seats, wagon enclosures, doors, windows, etc.

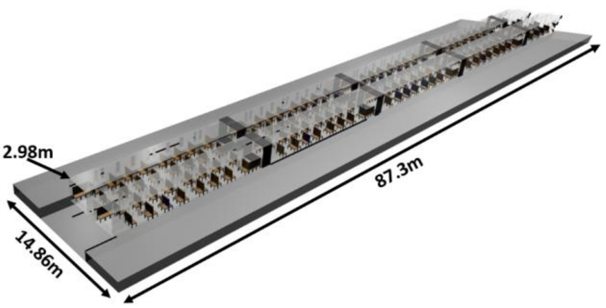

Fig. 1. Schematic representation of the inter-train communication scenario under analysis, which represents an urban train landing platform, with two trains located within the train station.

In order to analyze wireless channel performance of different communication systems which can be integrated within the inter-train scenario, a specific transmitter location has been included within the scenario. The location can be modified in order to consider any potential transmitter node, a task that can be further undertaken within a system deployment design and optimization phase as required. In this case, a central position within the rooftop of the train convoy has been chosen. The operating frequency has been subsequently varied in order to consider the potential use of different systems such as LPWAN, WLAN and 5G NR Frequency Range 1 (i.e., below 6 GHz) communication systems. Estimation of received power levels have been obtained for the complete volume of the scenario under test. In order to provide a comprehensive overview, results have been particularized for different cut plane heights (2 m, 3.5 m and 6 m). The results obtained for each one of the frequencies under consideration (*f@868 MHz, f@2.4GHz, f@3.5GHz, f@5.6GHz)* are depicted in figures 2 to 5, for each one of the 3 cut plane heights. The results show that propagation losses increase as frequency increases, which is inherent to the frequency dependent nature of path loss estimation. In relation with cut-plane height variations, the highest received power level distributions are given for cut-plane heights of 3.5m. This is given by the fact that fading effects owing to non-line of sight links are stronger in the case of lower height (i.e., h=2 m), whereas distance effects are larger as distance increase (h = 6m). It is worth noting that despite the relatively small distance differences, variations in received power level distributions are non-uniform, affected by the surrounding environment (i.e., train structure). In this sense, the main propagation mechanisms are given by shadowing by the train wagons, as well as by multi-path propagation effects, supported by the large density of scatterers present within the scenario under analysis.

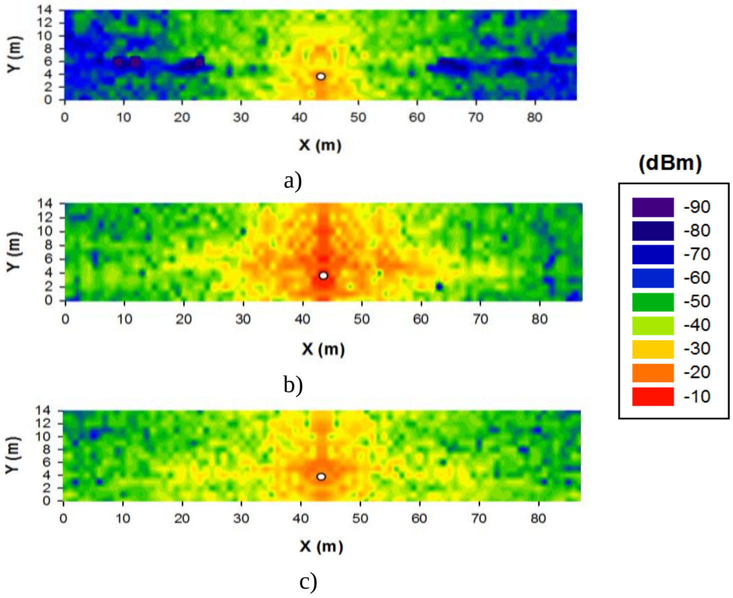

Fig. 2. Estimation of received power level distribution, with a frequency of operation of *f@868 Mhz* within the inter-train scenario, based on volumetric 3D Ray Launching approximation, for different 2D cut-plane heights: a) cut plane height = 2m, b) cut plane height = 3.5m, c) cut plane height = 6m

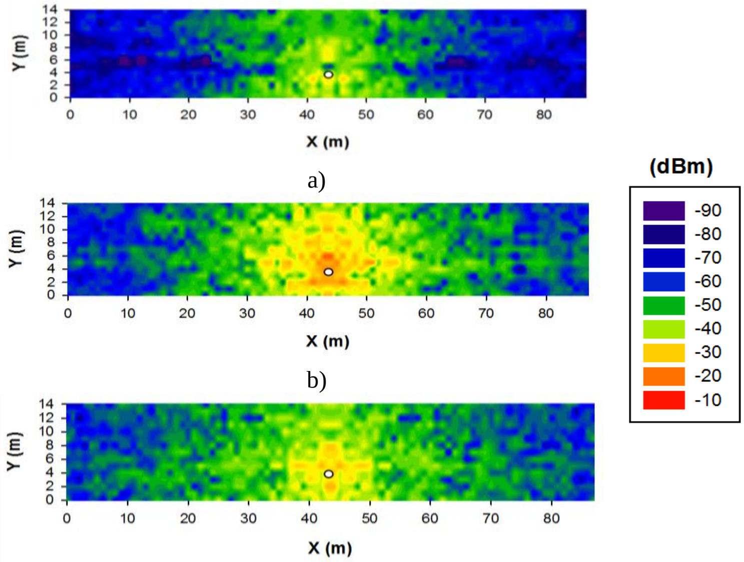

Fig. 3. Estimation of received power level distribution, with a frequency of operation of *f@2.4 Ghz* within the inter-train scenario, based on volumetric 3D Ray Launching approximation, for different 2D cut-plane heights: a) cut plane height = 2m, b) cut plane height = 3.5m, c) cut plane height = 6m

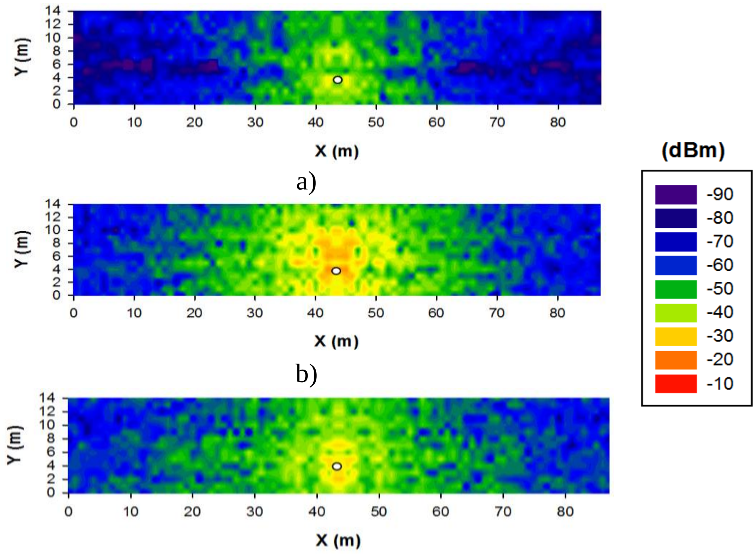

Fig. 4. Estimation of received power level distribution, with a frequency of operation of *f@3.5 Ghz* within the inter-train scenario, based on volumetric 3D Ray Launching approximation, for different 2D cut-plane heights: a) cut plane height = 2m, b) cut plane height = 3.5m, c) cut plane height = 6m

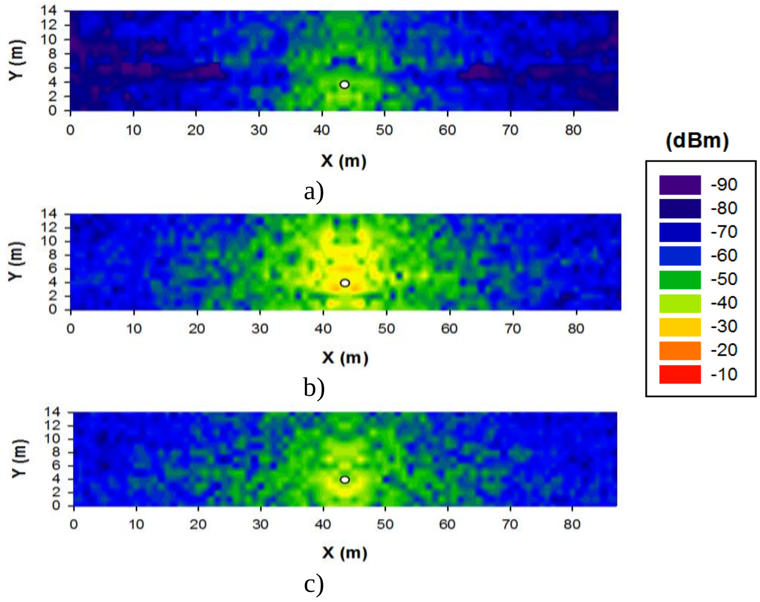

Fig. 5. Estimation of received power level distribution, with a frequency of operation of *f@5.6 Ghz* within the inter-train scenario, based on volumetric 3D Ray Launching approximation, for different 2D cut-plane heights: a) cut plane height = 2m, b) cut plane height = 3.5m, c) cut plane height = 6m

From the previous results, it can be seen that received power level distribution is strongly influenced by the surrounding environment, given mainly by the presence of multiple scatterers, which give rise to shadowing losses owing to non-line of sight links as well as to multipath propagation phenomena. The later can be observed by considering linear transmitter to receiver radials, in which strong dips given by fast fading components are present. These effects can be seen in fig. 6, where different TX-RX linear radials have been obtained, as a function of frequency of operation and observation height.

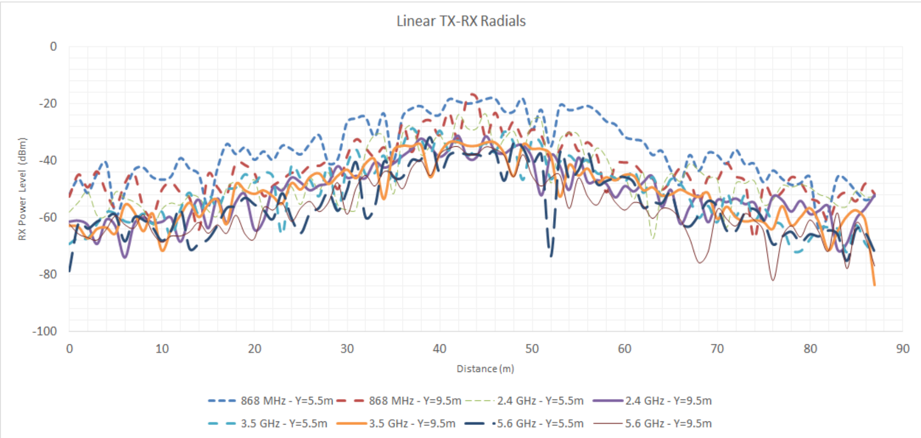

Fig. 6. Representation of different TX-RX linear radials of received power level distributions, as a function of frequency and height. Fast fading effects can be observed, owing to multipath propagation components within the inter-train wagon scenario.

In order to gain insight in relation with the effect of multipath components, time domain analysis results have been obtained with the aid of 3D Ray Launching simulation code. Power delay profiles (PDP) for different locations within the inter-train scenario, specifically for three different arbitrary positions of potential transceivers. The PDP represent all the time domain components detected within the receiver volume, which is given equivalently by the corresponding cuboid within the simulation scenario. The results obtained for each one of the observation points is depicted in fig. 7. As it can be seen, variations can be seen in relation with the time domain components, leading to delay spreads ranging from approximately 100ns to over 1100ns, as a function of the observation points. This is given by the distribution of scatterers, which in term define the field components that propagate within the inter-train scenario and which can be employed in order to analyze system dependence on coherence time and on the definition and design of channel equalization elements.

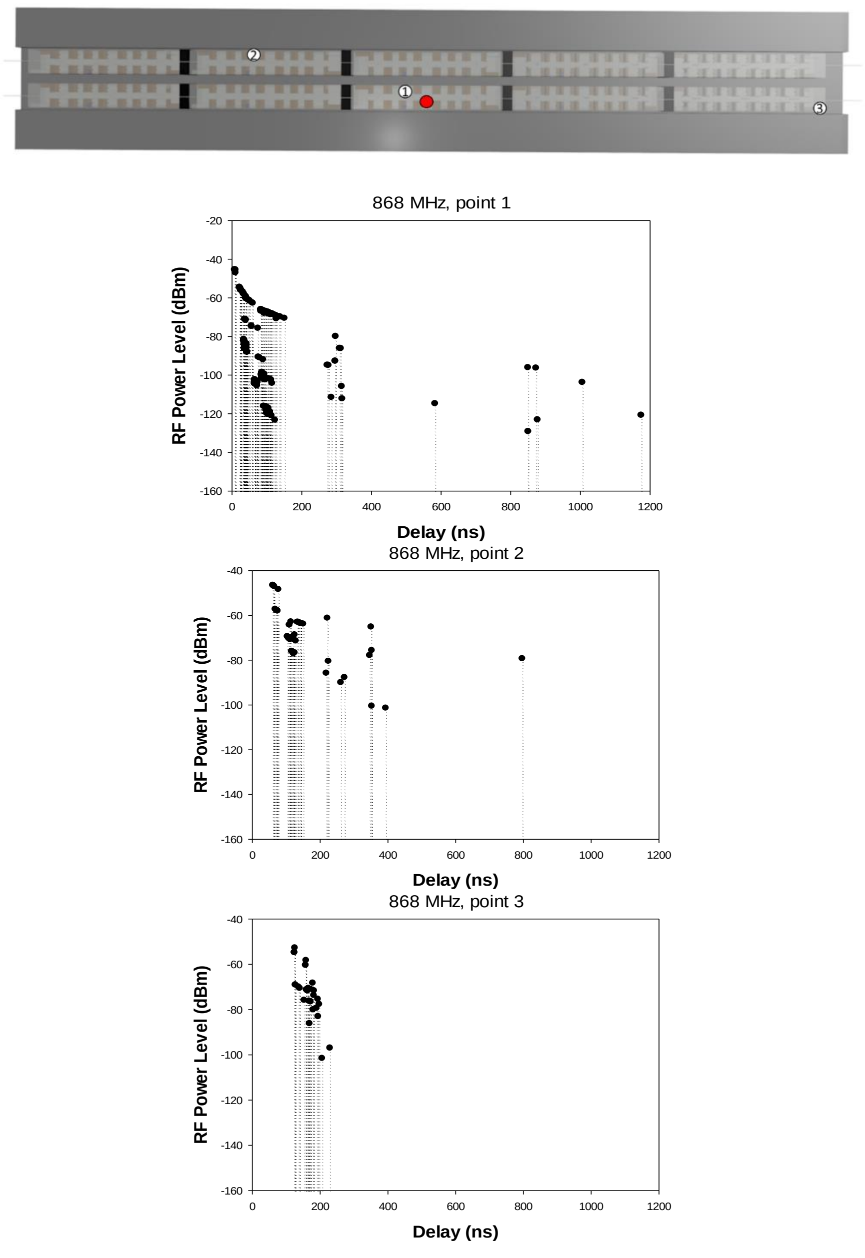

Fig. 7. Estimation of power delay profiles, with a frequency of operation of *f@868 Mhz* within the inter-train scenario, based on volumetric 3D Ray Launching approximation, for 3 different locations (points 1, 2 and 3, as depicted in the schematic scenario description provided in the top image).

3 Conclusions

The implementation of context aware environments within train applications takes advantage of the connection capabilities delivered by wireless communication systems. The presence of the train wagons as well as by the surrounding infrastructure determine the performance of wireless communication systems, in terms of path loss as well in time domain characteristics. Wireless channel behavior in power/frequency distributions as well as time domain characterization results have been obtained with the aid of deterministic 3D RL simulation method, providing results for the complete volume of the scenario under test. The proposed simulation technique provides precise coverage/capacity estimations, which can be employed in order to optimize network design and implementation phases.

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