WINNER model for subway tunnel at 5.8 GHz

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Abstract—**Modern subways operation relies on wireless systems based on IEEE802.11x modems deployed inside tunnels. Constraints on robustness and needs for high data rates led to the use of MIMO techniques. In order to evaluate performance of MIMO systems in dynamic configurations with moving trains, it is mandatory to develop adequate dynamic channel model. In this paper, the authors present a new WINNER based model for a subway tunnel at 5.8 GHz in a representative geometric configuration with two tracks and two crossing trains and a 4x4 MIMO system. The statistical behavior of the key parameters of the new WINNER scenario are derived from the complex impulse responses obtained with a 3D ray tracing simulator and given in this paper. Five clusters are considered. The total received power and the 4x4 MIMO channel capacity are compared with the ones derived from the 3D ray tracing simulator.**

Keywords-WINNER, Multiple Input-Multiple Output (MIMO), electromagnetic propagation, 3D ray tracing, channel capacity, tunnels

I. INTRODUCTION

Modern subways and particularly driverless systems use Communications Based Train Control (CBTC) systems that rely on continuous radio communications in the 2-6 GHz band. These systems are based on COTS (Component Of The Shell) such as IEEE 802.11x modems on which proprietary modifications have been implemented in order to guaranty Key Performance Indicators (KPI) related to availability, robustness of the radio links, end to end Quality of Services (QoS), handover duration, latency, etc. Today, MIMO (Multiple Input-Multiple Output) techniques have proven their ability to increase robustness or data rate and are implemented in emerging standards such as IEEE 802.11n, WiMAX, LTE. Nevertheless, important degradation of performance can occur in subway tunnels when there is spatial correlation in the channel [1][2]. In order to develop new MIMO algorithms able to cope with dynamic behavior of the channel (correlation but also moving trains), it is necessary to develop MIMO channel models easy to implement and able to accurately describe the dynamic channel behavior in subway tunnels when trains are moving. In this paper we present a new channel model based on the WINNER (Wireless World Initiative New Radio) model principle developed for a realistic dynamic subway scenario. The construction of this new model is performed thanks to time and frequency channel characterization using a 3D ray tracing simulator. The paper is organized as follows. The general principles of the WINNER model are given in section II. Section III presents the dynamic subway scenario and the methodology to feed the WINNER model is explained. Section IV presents the characteristics of the WINNER model obtained. The results in terms of 4x4 MIMO channel capacity and total received power in the tunnel are compared with the results directly derived from the 3D ray tracing model. Finally conclusions and perspectives are set up in section V.

II. THE WINNER MODEL

The WINNER model is a geometrical stochastic model that can be seen as an extension of channel models, such as 3GPP-SCM and IEEE 802.11 TGn, dealing respectively with outdoor and indoor scenarios [3]. It is considered in the literature as one of the most mature and complete [4][5]. It allows to model MIMO channels with time variations. Eighteen typical propagation scenarios including railway one exist operating between 2 and 6 GHz with a frequency band up to 100 MHz. None of them deals with tunnel environments. Matlab codes are available in [6]. As described in Figure 1, the channel is described as a sum of multiple paths organized in clusters (6 to 20) [5]. Each cluster associates paths with similar propagation characteristics. Each cluster is characterized by its delay (τ_n), its power (P_n) and the angles of arrival (AoA) and departure (AoD) of each path in the cluster. The number of clusters will depend on the chosen scenario.

The WINNER model is generally built from channel sounding campaigns or Ray tracing simulations. Each channel parameter is stochastically computed from statistical laws obtained from the measurements or the simulations. The channel model is described by its double directional complex impulse response (CIR) to translate the physical behavior of the channel independently of the antennas configurations. The channel coefficients $h_{u,s,n}(t,\tau)$ (t stands for the time and τ for the delay) for each cluster n and each pair of transmitting and receiving antennas respectively s and u can be written as (1). All the details to obtain the expression of $h_{u,s,n}(t,\tau)$ are given in [7]. The **F** vector corresponds to the antenna radiation pattern. $\mathbf{r_s}$ and $\mathbf{r_u}$ correspond to the position vector respectively of transmitters and receivers; $\phi_{n,m}$ stands for the angle departure in azimuth of path m in cluster n and $\varphi_{n,m}$ stands for the angle of arrival in azimuth of path m in cluster n. The position vectors and the angles of arrival and departure are linked by the following scalar products (2) and (3):

$$h_{u,s,n}(t,\tau)=\sqrt{\frac{P_n}{M}}\sum_{m=1}^{M}\begin{bmatrix}F_{u,V}\\F_{u,H}\end{bmatrix}^T \times \overbrace{\begin{bmatrix}\exp(j\Phi_{n,m}^{VV}) & \sqrt{\kappa_{n,m}}\exp(j\Phi_{n,m}^{VH})\\ \sqrt{\kappa_{n,m}}\exp(j\Phi_{n,m}^{HV}) & \exp(j\Phi_{n,m}^{HH})\end{bmatrix}}^{\text{2x2 polarisation matrix}} \times \begin{bmatrix}F_{s,V}\\F_{s,H}\end{bmatrix} \times \exp(j2\pi\lambda_0^{-1}\underbrace{\mathbf{r_s}\cdot\boldsymbol{\phi}_{\mathbf{n,m}}}_{\text{from Tx}})\times\exp(j2\pi\lambda_0^{-1}\underbrace{\mathbf{r_u}\cdot\boldsymbol{\varphi}_{\mathbf{n,m}}}_{\text{from Rx}})\times\exp(j2\pi v_{n,m}t)\delta(\tau-\tau_n) \quad (1)$$

$$\mathbf{r_s}\cdot\boldsymbol{\phi}_{\mathbf{n,m}} = x_s\cos(\Psi_{n,m})\cos(\phi_{n,m}) + y_s\cos(\Psi_{n,m})\sin(\phi_{n,m}) + z_s\sin(\Psi_{n,m}) \quad (2)$$

$$\mathbf{r_u}\cdot\boldsymbol{\varphi}_{\mathbf{n,m}} = x_u\cos(\gamma_{n,m})\cos(\varphi_{n,m}) + y_u\cos(\gamma_{n,m})\sin(\varphi_{n,m}) + z_u\sin(\gamma_{n,m}) \quad (3)$$

$\nu_{n,m}$ corresponds to the Doppler frequency of path m of cluster n and is expressed as (4):

$$\begin{aligned}v_{n,m} &= \frac{\mathbf{v}\cdot\boldsymbol{\varphi}_{\mathbf{n,m}}}{\lambda_0} \quad (4)\\ &= \frac{|v|\cos(\theta_v)\cos(\gamma_{n,m})\cos(\varphi_{n,m}) + |v|\sin(\theta_v)\cos(\gamma_{n,m})\sin(\varphi_{n,m})}{\lambda_0}\end{aligned}$$

The complex MIMO channel matrix **H** of size UxS is given by:

$$\mathbf{H}(t,\tau)=\begin{bmatrix} h_{1,1}(t,\tau) & \dots & h_{1,2}(t,\tau) & \dots & h_{1,S}(t,\tau)\\ h_{2,1}(t,\tau) & \dots & h_{2,2}(t,\tau) & \dots & h_{2,S}(t,\tau)\\ \vdots & & \vdots & & \vdots\\ h_{U,1}(t,\tau) & \dots & h_{U,2}(t,\tau) & \dots & h_{U,S}(t,\tau)\end{bmatrix} \quad (5)$$

where $h_{u,s}$ corresponds to the channel CIR between antenna u and s. Each $h_{u,s}$ is composed by a number of n clusters (n=1,…,N) and is computed following (6):

$$h_{u,s}(t,\tau)=\sum_{n=1}^{N} h_{s,u,n}(t,\tau) \quad (6)$$

All the parameters of the channel model are obtained using the outputs of a 3D ray tracing based model [8]. Due to the complexity of the railway scenario for a MIMO system with moving trains, an accelerating method to compute the CIR has been developed. The method is described in [9]. All the main paths between the transmitters and the receivers are characterized by the following information: power, delay, AoA and AoD in azimuth and elevation. Then a method has been specifically developed to extract the dynamic information such as Doppler spectrum and the statistic laws describing the channel behavior [10].

III. WINNER SCENARIO FOR SUBWAY TUNNELS

A. *The methodology*

The aim is to obtain the channel coefficients for each SISO (Single Input-Single Output) link. They are obtained following several steps presented in the diagram given in figure 2. The WINNER model considers a stochastic model common to all the existing scenarios for which the parameters of the statistical laws are classified in look up tables. In the general WINNER model, the number of clusters can vary from 6 to 20 as a function of the considered scenario. The angles follow a Gaussian distribution (We will see later that it is not the case for the tunnel scenario). The delays follow an exponential distribution except for the B1 (Urban micro cell) scenario. The details for all the different steps are given in [11].

The cluster identification process is based on the *k*-means algorithm [12]. The distance intra cluster is minimized whereas the distance inter cluster is maximized. The quality of the classification is evaluated using the "silhouette" algorithm [13] and the optimal number of clusters is identified. Finally the statistical laws that describe the behavior of each parameter of the cluster (power, path loss, delays, AoA and AoD in azimuth and elevation) are identified using an information criteria based method [14].

B. *The chosen underground scenario for simulations*

The chosen scenario for the ray tracing simulations corresponds to a realistic case with a two tracks tunnel and two trains. We consider a 4 x 4 MIMO system. One train is parked under the antennas hanged on the ceiling of the tunnel and the other train is moving towards the parked train. The 4 receiving antennas are fixed on the top of the moving train. We consider vertical elementary dipoles. Figure 3 gives a schematic view of the scenario.

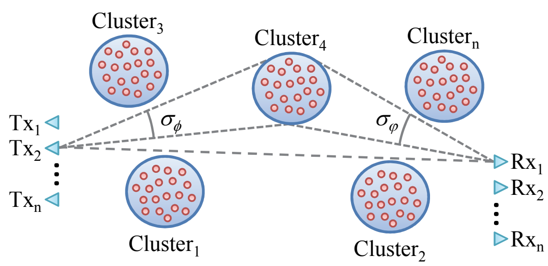

Figure 1. Illustration of a group of clusters representing the radio channel

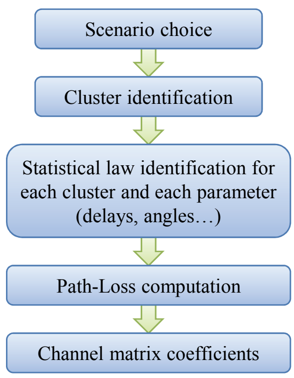

Figure 2. Followed methodology

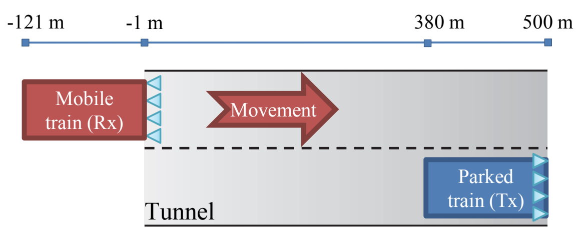

Figure 3. Chosen Railway scenario

The CIR are computed every λ/3 at 5.8 GHz. The properties of the tunnel and the trains are given in table I. The speed is equal to 50 km/h. These parameters involve 29 471 simulations.

The transmitted power equals 1 mW. The antenna elements are 10 λ spaced in order to avoid spatial correlation and coupling. The chosen number of electromagnetic interactions equals six reflections and one diffraction. The channel is considered WSSUS over 10 λ [15].

TABLE I. TUNNEL AND TRAINS CHARACTERISTICS

	Dimensions (x,y,z) m^3	Electromagnetic characteristics (ε_r and σ)
Tunnel	9 x 500 x 4.5	$\varepsilon_r = 10$, $\sigma = 0.1$ S.m^{-1}
Both trains	3 x 120 x 4	$\varepsilon_r = 1$, $\sigma = 56000$ S.m^{-1}

IV. WINNER MODEL PARAMETERS FOR THE SUBWAY SCENARIO

In the following, we present the results obtained with the methodology described to build the WINNER model for the chosen scenario given in figure 3.

A. *Optimal number of Clusters*

The optimal number of clusters identified for this scenario is equal to 5 and the total number of paths in each cluster is given in table II.

TABLE II. NUMBER OF PATHS IDENTIFIED FOR EACH CLUSTER ALONG THE TUNNEL

Cluster	C_1	C_2	C_3	C_4	C_5
Total number of paths	933264	928655	293332	1078804	2499873

B. *Path loss in each cluster*

For each cluster n we computed the path loss PL_n as a function of transmitter-receiver distance d given by:

$$PL_n = A_n + B_n \log(d) \quad (7)$$

where A_n and B_n are given in dB. Table III summarizes the values of A_n and B_n coefficients for each cluster C_n.

TABLE III. A_n AND B_n COEFFICIENT FO EACH CLUSTER (IN DB)

Cluster	A_n	B_n
C_1	-84.16	-3.25
C_2	-73.49	-5.37
C_3	-60.01	-9.21
C_4	-70.69	-5.57
C_5	-52.76	-7.33

C. *Fast fading behavior*

The next step consists in the identification of the statistical laws and corresponding parameters to model the fast fading for each cluster C_n. The results are given in table IV.

TABLE IV. STATISTICAL LAWS AND ASSOCIATED PARAMETERS TO MODEL FAST FADING IN EACH CLUSTER

Cluster	Law	1st parameter	2nd parameter
C_1	Log-normal	0	0.731
C_2	Nakagami	0.947	1.906
C_3	Log-normal	0.031	0.636
C_4	Gamma	2.547	0.491
C_5	Gamma	3.358	0.354

D. *Delays in each cluster*

The following table V summarizes the values for the parameters of the statistical laws to model the delays in each cluster in the case of the chosen scenario in tunnel.

TABLE V. STATISTICAL LAWS AND ASSOCIATED PARAMETERS TO MODEL DELAYS IN EACH CLUSTER

Cluster	Law	1st parameter	2nd parameter
C_1	Nakagami	0.127	15.642
C_2	Laplace	7.419	5.842
C_3	Laplace	3.191	3.881
C_4	Laplace	4.953	4.978
C_5	Laplace	2.459	2.819

E. *Statistical law for the angles for each cluster*

Table VI summarizes the values for the parameters of the statistical laws to model the AoA and AoD in azimuth and elevation in each cluster.

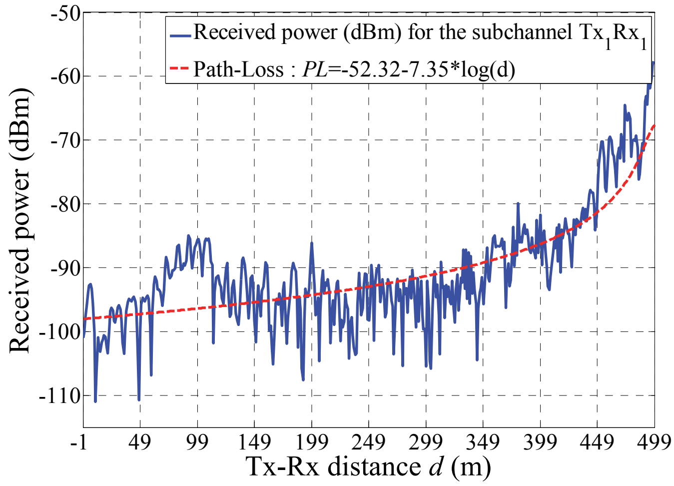

Figure 4. Received power for one SISO link versus transmitter-receiver distance

F. Generation of the channel coefficients

We model the power, the delays and the AoA and AoD in azimuth and elevation for each cluster in the tunnel of the chosen scenario (Figure 3). Now to compute the channel coefficients using equation (1), we fix an average number of predominant taps in each cluster. Table VII gives the average number of taps obtained in each cluster. We can observe that clusters 1, 2 and 4 contain approximately the same number of taps. Cluster 3 contains only 10 taps and cluster 5 can be considered as the larger cluster with 85 taps. At this stage we chose to fix the average number of taps per cluster equal to 40 that corresponds approximately to the average of the 5 values given in table VII. We remind that in the literature, the average number of taps per cluster is equal to 20 for the other scenarios of the WINNER model.

TABLE VI. AVERAGE NUMBER OF TAPS PER CLUSTER

Cluster	C_1	C_2	C_3	C_4	C_5
Average number of taps	32	32	10	37	85

G. Mean attenuation and standard deviation of fast fading

The last step consists now in the evaluation of the statistical law and associated parameters for the fast fading of the total received power for all the clusters along the tunnel. We consider each SISO link as indicated in figure 4. The following table VIII summarized the results.

TABLE VIII. PARAMETER AND STATISTICAL LAW FOR THE FAST FADING

Law	**1st parameter**	**2nd parameter**
gamma	2.52	0.498

V. EVALUATION OF THE CHANNEL MODEL PROPOSED

In this section we evaluate the performance of our WINNER based channel model for a new scenario in subway using two main parameters: the total power versus the distance in the tunnel and the 4x4 MIMO channel capacity computed using equation (8). The results obtained with our model are compared with the results directly computed from the CIR at the output of the 3D ray tracing based simulator.

A. Received power

The total received power in the tunnel computed with our WINNER based model is drawn in red on Figure 5 and compared to the results obtained with the 3D ray tracing based tool (in blue). The difference between the curves is very small. Figure 6 shows the cumulative distribution function of the total power. The curves are very close and confirm the good agreement between the two models.

B. MIMO channel capacity

We now compare the MIMO channel capacity obtained by:

$$C = \log_2\left[\det\left(\mathbf{I}_U + \frac{\rho}{S}\mathbf{H}^H\mathbf{H}\right)\right] \qquad (8)$$

where **H** is the MIMO channel matrix of size UxS, with U and S the number of antennas at the receiving and the transmitting sides, respectively, $\mathbf{I}_U$ stands for the identity matrix of size UxU, and ρ is the signal to noise ratio (SNR).

Figure 7 and 8 show that the curves obtained with the two models are very close.

VI. CONCLUSION

Today there is no available MIMO channel model to describe the behavior of dynamic subway scenario in tunnel from a radio channel point of view in order to evaluate digital communication systems. In this work we presented a new geometric stochastic model developed using the strategy and methodology of the WINNER model based on the information coming from a 3D ray tracing based tool used to simulate all the propagation paths in a given realistic dynamic scenario with two tracks and two trains (one is moving).

We have shown that the optimal number of clusters is equal to 5 and we have studied the evolution of these 5 clusters in the tunnel. Then we have identified the statistical laws describing the behavior of the different characteristic parameters of the channel (power, delays, AoA and AoD in azimuth and elevation). The number of taps in each cluster is fixed to 40. Finally we have computed the channel coefficient $h_{u,s}$ for each pair of antennas. The total received power and the 4x4 MIMO channel capacity are computed with the new channel model coefficients and compared to the values obtained with the 3D ray tracing based model. The results obtained with the WINNER model are very close to the ones obtained with the deterministic model.

TABLE VII. STATISTICAL LAWS AND ASSOCIATED PARAMETERS TO MODEL ANGLES IN EACH CLUSTER

Cluster	C_1		C_2		C_3		C_4		C_5	
Law	**Laplace**		**Laplace**		**Laplace**		**Laplace**		**Laplace**	
Parameters	μ	b	μ	b	μ	b	μ	b	μ	b
φ(°)	-1.23	4.28	9.47	5.28	-3.08	10.77	-10.26	8.11	-1.25	4.55
γ(°)	61.76	0.87	-0.09	0.56	-0.08	0.60	0.02	0.48	0.37	0.58
ϕ(°)	0.83	4.70	-9.13	5.40	2.62	9.66	-4.62	5.60	3.45	4.95
ψ(°)	-0.17	0.89	-0.47	0.93	-4.23	2.66	-0.22	0.73	0.08	0.89

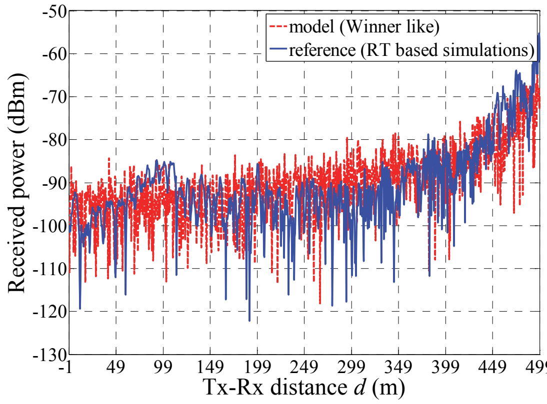

Figure 5. Received power obtained with the model and the 3D ray tracing tool versus the distance in the tunnel

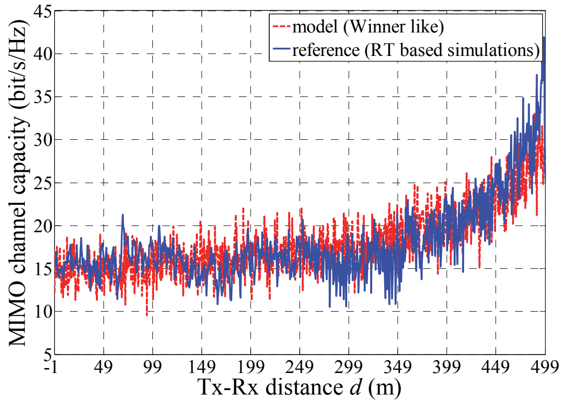

Figure 7. 4x4 MIMO chanel capacity versus the distance in the tunnel comuted using (x) with the two models

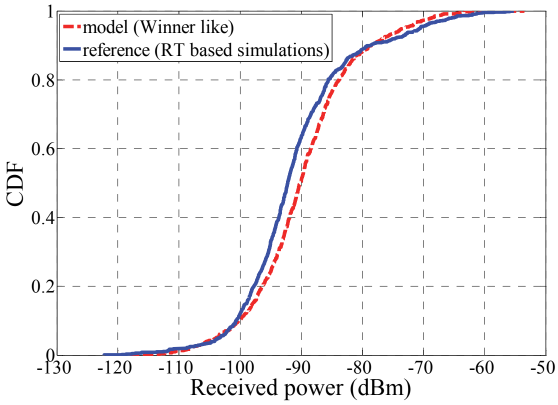

Figure 6. Cumulative Distribution Function (CDF) of the received power obtained with the model and the ray-tracing based simulation results

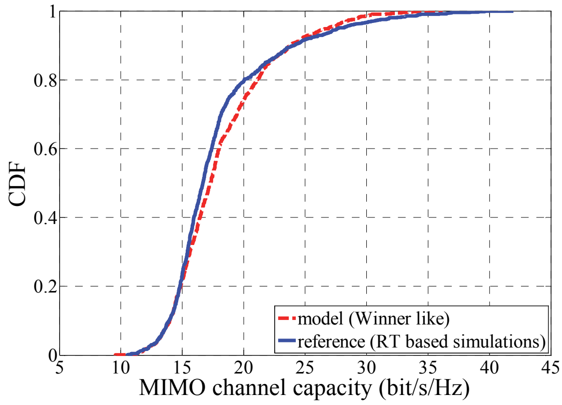

Figure 8. Cumulative Distibution Function of the 4x4 MIMO channel capacity from the channel model and the ray-tracing based simulation results

We can highlight two main perspectives of this work. First we will apply this methodology to other operational subway scenarios using the 3D ray tracing based model but also measurement results obtained in real tunnels.

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