ESPAR Antenna Positioning for Truck-to-Truck Communication Links

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***Abstract*—This work investigates various antenna configurations for Truck-to-Truck (T2T) communication links used for Intelligent Transportation Systems (ITS). T2T links are very challenging, since the trailer may destructively affect the system performance. In addition, the use of two 3-element ESPAR antennas positioned on the truck side mirrors is proposed. The proposed configuration achieves significant performance improvement with the use of simple beam selection implemented with ON-OFF switching. Simulation results using the IST-WINNER channel model for T2T links are presented, that verify the suitability of the 3-element ESPAR for the specific application.**

***Index Terms*—antenna position, ESPAR, trucks, T2T.**

I. Introduction

The performance of the Intelligent Transportation Systems (ITS) depends on the quality of the inter-vehicular link for Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication systems. V2V/V2I communications present specific challenges due to the fact that: i) both transmitter (Tx) and receiver (Rx) are located at the same height, ii) significant scattering is presented at both Tx and Rx since many metallic surfaces are in the close proximity of the antennas, iii) high speed movement is expected for the Tx and/or Rx vehicles, iv) low-power wideband signals are transmitted, v) the distance range between Tx and Rx may vary significantly [1].

The main requirement for ITS applications is the establishment of highly reliable links, since safety messages may be continuously transmitted by the vehicles. In these systems, the position of the antennas on the vehicle plays a highly essential role, since the vehicle itself may destructively affect the transmission. Diversity techniques may improve the performance of the link as presented in [2]- [3]. The problem of link reliability becomes even more crucial in Truck-to-Truck (T2T) communications, since the truck trailer may cause even more significant connectivity issues.

This paper uses a simple truck model in order to investigate the effect of the antenna position in T2T links. Two antennas for each vehicle are used for ITS communications located either on the roof of the truck cabin or the truck side mirrors. Furthermore, the use of an Electronically Switched Parasitic Array Radiator (ESPAR) antenna with beam selection capabilities is proposed in order to improve link performance. The simulated results are very promising since significant improvement is achieved in both Rx Signal-to-Noise Ratio (SNR) as well as the Average Bit Error Probability (ABEP) with the use of the proposed antenna configuration. In Section II, the developed Antenna-Truck model is presented. In Section III, evaluation of the investigated antenna configurations is performed using the IST-WINNER channel model. Finally, in Section IV conclusions are derived.

II. The Antenna - Truck Model

In order to evaluate the antenna performance in various T2T communication links over a realistic propagation environment, three appropriately designed antenna - truck model combinations were developed. The antenna - truck models are implemented in the CST 3D electro-magnetic simulator [4]. Specifically, the three combinations involve two different types of antennas (single monopole, 3-element ESPAR) that are accurately modeled, investigated and simulated along with a truck and trailer in two different positions (roof and side mirrors), with the intention to produce representative far-field patterns. Consequently, the simulated antenna patterns are imported into the IST-WINNER MATLAB model in order to evaluate a realistic propagation scenario.

A. Truck - Trailer model

The truck - trailer design is mainly based on the ”TGX - XLX International - National Long-haul Sleeper” model by MAN. Practically, it corresponds to a profoundly simplified version of the actual model that merely satisfies the basic dimensions and the main materials that are employed for the truck manufacture. In addition, two layers of asphalt and dry soil are placed underneath the truck - trailer in order to emulate the high-way environment. Fig. 1 illustrates the truck - trailer model as it was designed in CST. This high degree of simplification was proved to be necessary in order to preserve the memory usage (meshing) and the simulation duration in fairly low levels. However, special attention was given on the selection of the materials and their correspondence to the correct truck components, especially for the ones that are located in the antenna's proximity. Table I includes a list of the materials used in the model along with the equivalent truck parts and dielectric constant values. The basic dimensions of the truck - trailer design are given in Table II in mm.

B. Antenna Designs

This section provides a brief description of the two antenna designs (single monopole, 3-monopole ESPAR) that are employed in the IST-WINNER implementation and are designed to operate at 5.9 GHz. Fig.2 demonstrates their layout.

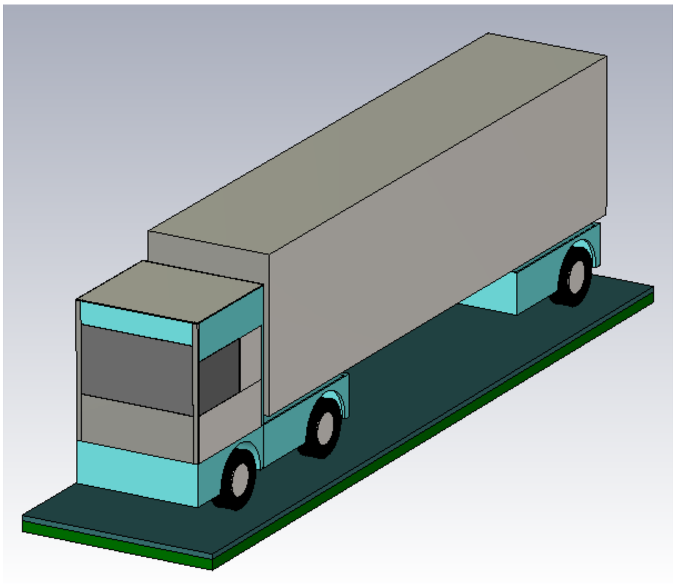

Fig. 1. The truck - trailer design model along with the high-way part underneath it.

TABLE I
TRUCK - TRAILER MATERIALS

Material	***Truck Components***	ϵ_r
PEC (metal / steel)	cabin body (chassis), roof, pillars, doors, hubcaps, trailer	infinite
plastic (polyethylene)	Bumpers, top front and side parts of cabin	2.25
glass (Pyrex)	Front and side windows	4.82
rubber	tires	3
asphalt	-	2.6
dry soil	-	2.27

The first antenna design is a simple monopole radiator located above a circular ground plane of 50 mm diameter. The radius of the metal pin is equal to 0.7 mm and its length reaches up to 10.9 mm. The pin is fed by a co-axial line (waveguide port) composed by a Teflon inner layer and a PEC outer layer. As it is illustrated in Fig. 3, the monopole demonstrates a satisfying return loss (-41 dB at 5.9 GHz) and a remarkably wide operating bandwidth over 28%. The top-view ($\theta = 90^o$) far-field pattern cut that is presented in Fig. 4, confirms the monopole' s omni-directional behavior.

TABLE II
BASIC TRUCK DIMENSIONS

Description	***Dimension***
overall cabin height	3,895
front overhang	1,475
exterior cabin width	2,440
exterior cabin length	2,280
trailer length	12,000
trailer width	2,440
tire radius	537
tire width	318

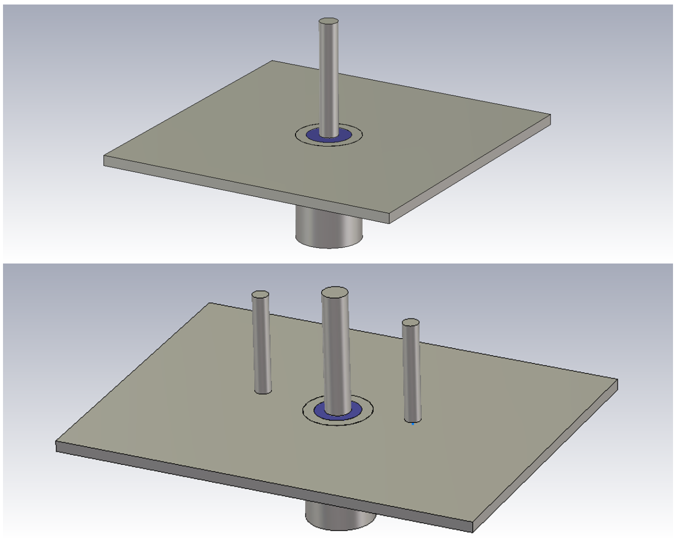

Fig. 2. Layout of the single monopole and the 3-monopole ESPAR antennas, demonstrating their simple geometry.

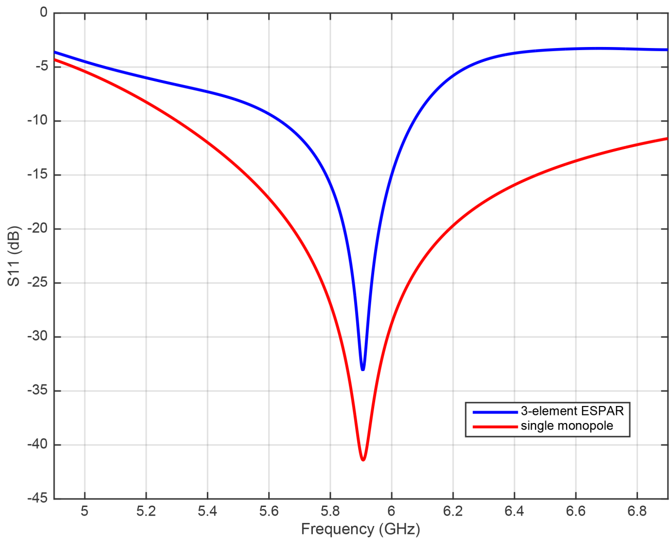

Fig. 3. Return loss of the single monopole and the 3-element ESPAR.

The second design corresponds to a 3-element ESPAR antenna. The ESPARs exhibit significantly reduced complexity compared to other Multiple-Input-Multiple-Output (MIMO) systems with multiple RF-chains and considerable inter-element distances [5], [6], [7]. ESPARs are able to operate with only one active element, and as a result, with a single RF-chain, while preserving the majority of the features of a MIMO system, such as beam-forming and spatial multiplexing capability. The rest of the radiators that comprise the ESPAR antenna are passive parasitic elements that can be distributed around the active element in several arrangements and in extremely small distances ($\lambda/5 - \lambda/16$). This leads to the second main advantage of the ESPARs, which is their fitness

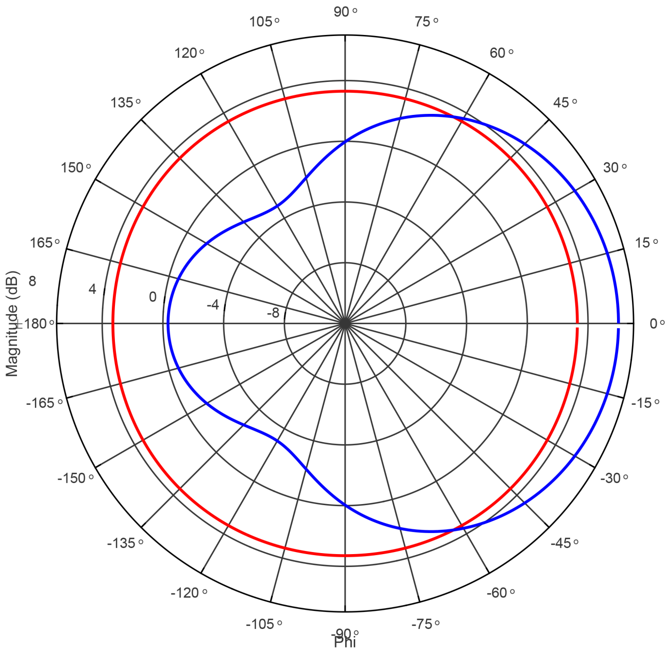

Fig. 4. The far-field radiation patterns of the single monopole antenna (red) and the 3-monopole ESPAR (blue) at the $\theta = 90^o$ plane (top-view).

and applicability in cases where severely limited space is available, e.g. inside the side mirror of a vehicle.

In the investigated case, the ESPAR is based on the preceding monopole radiator and is composed by three monopole radiators (one active and two parasitics) in a linear configuration. The parasitic elements are placed in a $\lambda/6$ distance away from the active radiator. The required objective of the antenna structure is to achieve a reconfigurable far-field pattern, i.e. the ability to change the direction of its radiation pattern from one side to the opposite with simple ON-OFF switching of the parasitic monopoles. Switching so far is realized by short/open circuit. Nevertheless, future work will involve the use of p-i-n diodes and varactors. The dimensions of the active monopole are slightly re-adjusted in order to achieve a satisfactory impedance matching and obtain significantly low return loss. The dimensions of the parasitics are designed fairly smaller (shorter and thinner metal pin) than the active monopole with the intention to enhance the directivity of the array. Table III presents the dimensions of the 3-element ESPAR geometry.

As presented in Fig. 3, the operating -10 dB bandwidth of the ESPAR is considerably smaller than the monopole's, but it still remains in satisfying levels (400 MHz, almost 7%). The ESPARs radiation pattern, illustrated in Fig. 4, demonstrates the reconfigurability aspect of the antenna and indicates a considerable 2.9 dB directivity increase in the desired direction.

C. Antenna Truck Configurations

In order to investigate the issue of a suitable antenna position selection, two main location candidates, the roof of the truck cabin and the side mirrors, are selected and tested. The IST-WINNER channel model evaluation of the next section is carried out for the following three antenna-truck configurations:

- Two monopole radiators on the roof of the cabin, located in the middle point of the cabin length, separated by a 600 mm distance.
- Two monopole radiators at the position of the two side mirrors, 3,000 mm above the asphalt level and 400 mm beyond the edge of the truck cabin.
- Two 3-monopole ESPAR radiators at the position of the two side mirrors.

TABLE III
ESPAR DIMENSIONS

Parameter	***Description***	***Value (mm)***
L_m	length of the active monopole	10.85
radius	radius of the active monopole	1.05
diff	difference between active and parasitic lengths	1.5
dis	distance between active and parasitic	λ/6
gap	gap between parasitic and ground plane	0.5
rad	radius of the parasitics	0.7

Fig. 5 includes the three 3D directivity patterns for the three cases respectively. It is quite obvious that for the roof configuration, the obtained irregular pattern is mainly caused by the shielding of the metal trailer. Specifically, a significant part of the radiation is reflected on the trailer resulting in a critical restriction of the radiation, especially for the angles away from the azimuth plane. However, when the two monopole radiators are placed at the side mirror positions, the scatterers that are located in the really close proximity of the two radiators are reduced and the effect of the truck trailer system is reasonably decreased. Therefore, the directivity pattern seems to obtain a more isotropic characteristic. For the third case (ESPAR antennas), a significant part of the radiation is directed towards the corresponding desired direction (back direction for the leading truck, front direction for the following truck). This fact, combined with the Line of Sight (LoS) conditions, results in a substantial performance improvement.

III. Radio Channel Modeling

In order to evaluate the three presented configurations in Sec. II, simulation analysis was performed. Two trucks were assumed, equipped with an ITS G5 [8] system. ITS G5 physical layer is based on IEEE 802.11p [9] at 5.9 GHz carrier frequency with 10 MHz bandwidth. The two trucks are assumed to move on a highway crossing a rural area and both trucks move in the right lane of the highway. Moreover, they are moving in a straight line formation (no turns). The speed of the trucks was 70 km/h (approximately 20 m/sec). The radio channel model that was used for evaluation was the IST-WINNER2 channel model [10]. C1 channel models were

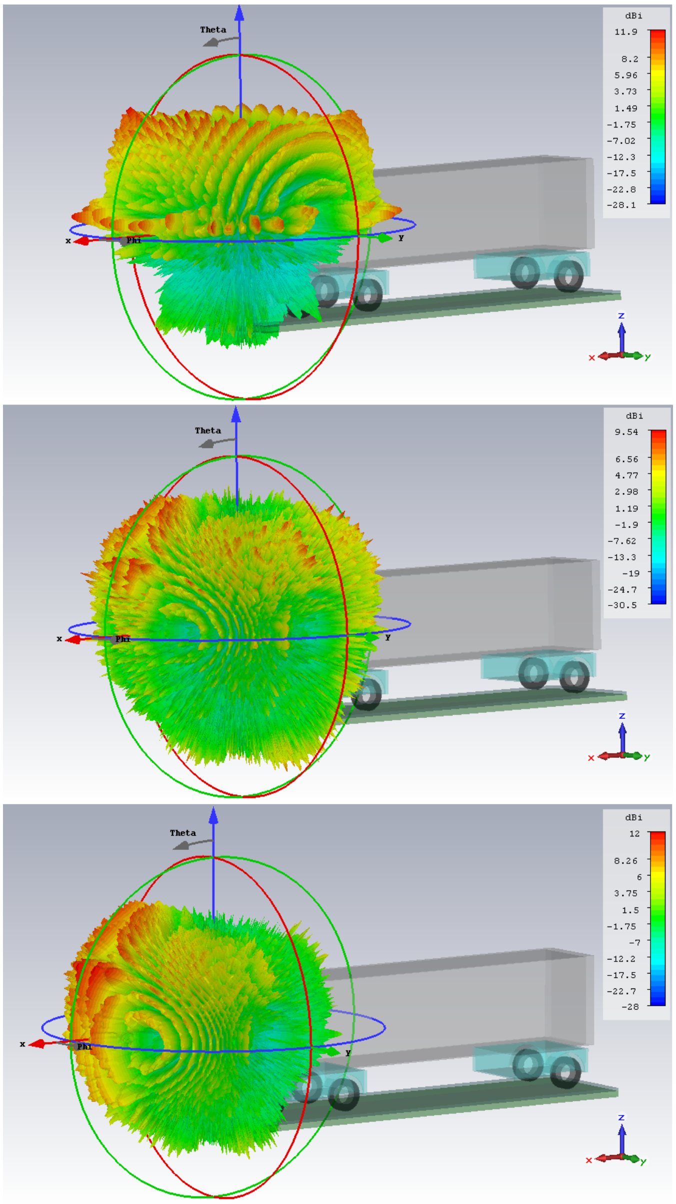

Fig. 5. The far-field directivity patterns for the three antenna truck configurations (monopoles on the roof, monopoles at the mirrors, ESPARs at the mirrors).

considered, which correspond to a rural macro-cell scenario. The patterns that were extracted in Sec. II were imported in the IST-WINNER2 channel using the modification of [11].

$$[\mathbf{H}_b(t;\tau)]_{i,i} = \sqrt{\frac{p(k)}{(K_{LoS}+1)N_k}} \cdot e^{j\sigma_{k,n}} e^{\frac{2\pi t\left(v_{\mathrm{Rx}}\cos\left(\zeta^{AoA}_{k,n}-\zeta_{v,Rx}\right)-v_{\mathrm{Tx}}\cos\left(\zeta^{AoD}_{k,n}-\zeta_{v,Tx}\right)\right)}{\lambda}} \delta_{\tau-\tau_k} \quad (1)$$

More specifically, $\mathbf{H}_b$ is a diagonal $(1+\sum N_k)\times(1+\sum N_k)$ matrix containing the complex path gains for all scatterers, where N_k is the number of rays for the $k-$th cluster of scatterers, v_{Tx}, v_{Rx} the Tx-Rx velocities, $\zeta^{AoA}_{k,n}$, $\zeta^{AoD}_{k,n}$ the angles of Arrival and Departure for the $n-$th ray of the $k-th$ cluster, $p(k)$ the path gains for each cluster ($p(0) = K_{LoS}$) and $\zeta_{v,Rx/Tx}$ the orientation of the Rx-Tx arrays. All angles are given with reference to the Global Coordinate System of the WINNER model. After the calculation of $\mathbf{H}_b$, the channel matrix is given by:

$$\mathbf{H} = \mathbf{P}^H_{rx}\mathbf{H}_b(t;\tau)\mathbf{P}_{tx} \quad (2)$$

where $\mathbf{P}'s$ are $(1+\sum N_k)\times 2$ matrices containing the patterns for each of the two Tx and Rx antenna elements towards the location of the scatterers. It is noted that the patterns in $\mathbf{P}$ should include phase differences due to the positioning of the antennas in the array (i.e. the steering matrix is applied to each element pattern).

Nevertheless, extra modifications of the channel model were needed in order to support mobility for both trucks (Tx and Rx) and aligned movement in a straight line with the antennas properly placed and rotated, at the correct height (Sec. II).

Since the objective of the paper is to evaluate the antenna configurations on the truck, no elaborate Tx or Rx diversity scheme was used. Diversity techniques will be study in future work. Thus, it is assumed that the ITS signal is transmitted simultaneously by both antennas of the Tx and it is combined with simple addition at the Rx antennas.

Three basic scenarios were investigated and simulated:

- The two antennas are mounted on the roof of both trucks.
- The two antennas are mounted on the side mirrors of the trucks
- Two 3-element ESPAR antennas are mounted on the side mirrors of the trucks. The preceding truck focuses the antenna beam to the back, while the following truck focuses the antenna beam to the front.

10,000 channels were simulated. The same set of channels was investigated for all three configurations. During each simulated session, 100 ITS G5 bursts of 1kByte packets were transmitted every 10 msec, in order to take into account the Doppler effects due to the high-speed mobility of the Tx and Rx. The transmitted power was 33 dBm (1W per element), which corresponds to the maximum allowed EIRP for an ITS system that uses the ITS G5 Control Channel (safety messages). The noise level at the Rx was assumed -118 dBm.

In Fig. 6 , the average Rx SNR vs. Tx-Rx separation distance is presented. It is clear that the SNR at the Rx significantly increases with the placement of the antennas at the side-mirrors. Moreover, additional SNR improvement is noticed with the use of a simple ESPAR antenna with ON-OFF elements. The SNR gain due to the use of ESPARs on the side mirrors reaches 10 dB for distances $>$ 250m compared with the performance of the system with roof mounted antennas

The Average Bit Error Probability (ABEP) is also extracted for the three configurations. The error rate is calculated assuming the basic ITS G5 transmission mode, with Binary Phase-Shift Keying (BPSK) modulation and 1/2 convolutional coding. The ABEP is calculated over the wideband system, i.e. over the 48 subcarriers that are used for data transmission in the Orthogonal Frequency-Division Multiplexing (OFDM)

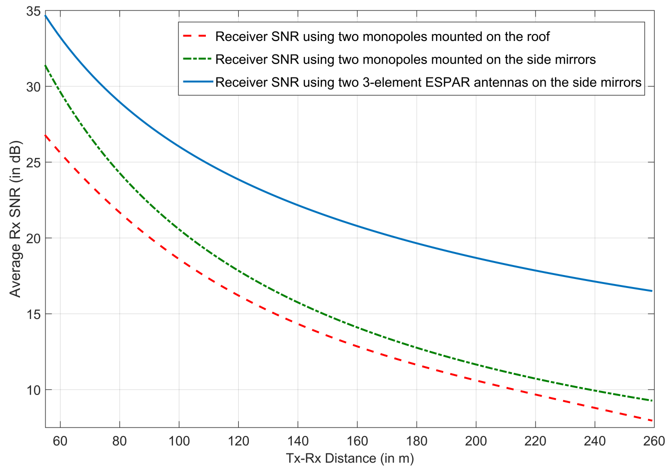

Fig. 6. Average SNR vs. distance for T2T C2 WINNER radio channels.

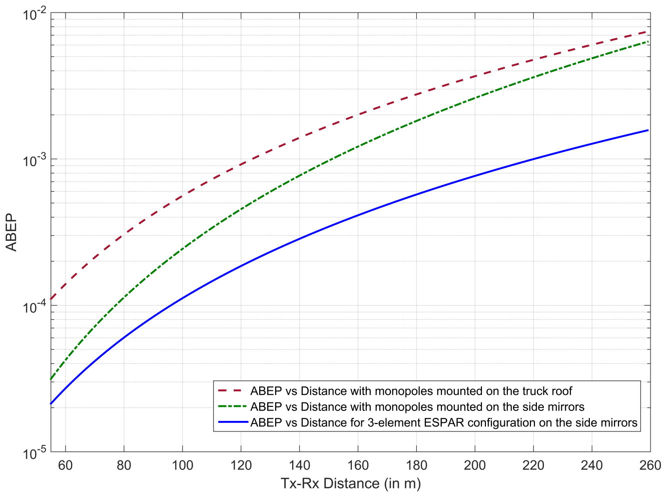

Fig. 7. ABEP vs. distance for T2T C2 WINNER radio channels.

IEEE 802.11p. In Fig. 7, the ABEP vs. Tx-Rx separation distance is plotted. It is noted that due to the frequency selectivity of the channel, the SNR per subcarrier may vary significantly relative to the average SNR. The improvement in the operation of the system when the antennas are placed on the side mirrors is impressive. In addition, the use of an ESPAR system will furthermore reduce the achieved ABEP. According to the simulation results, the ESPAR system performs better on average for Tx-Rx distance 120 m than the roof-mounted antenna system for Tx-Rx distance of 50 m.

However, it should be noted that the IST-WINNER2 model supports 2D propagation, therefore the effect of the 3D pattern is not fully taken into account. It is expected, due to the effect of the trailer on the pattern in the first scenario (Fig. 5), that the performance improvement from the placement of the antennas on the side mirrors will further increase.

IV. Conclusion

This paper proposes the use of a 3-element ESPAR antenna for T2T communication links. The new antenna configuration achieves significant performance improvement compared with the use of monopoles positioned either on the roof or the side mirrors of the vehicle. Evaluation was performed with the development of a truck-antenna model and the use of the IST-WINNER channel model. SNR improvement up to 10 dB was noted. In addition the ABEP performance of the links was significantly reduced.

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