Environment-based Roadside Unit Deployment for Urban Scenarios

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***Abstract*—Vehicular communications are increasingly gaining importance in research and industry as a viable communication technology, which makes cost-efficient and reliable deployment strategies a key aspect for the planning of a communication network infrastructure. The most critical aspect, and at the same time, the biggest challenge is to obtain a total connectivity between the vehicles and the network elements. In this paper, an environment-based deployment strategy is developed, obtaining an optimal number and distribution of RSUs in a selected area while maximizing the connectivity of the network. The main distinctive aspect of the proposed strategy is the use of an environment-based radio channel model, which is specific for a given urban area. Once the site-specific propagation parameters of the proposed radio channel model are obtained, the optimal RSU distribution is achieved by solving a multi-objective, integer linear program. In addition, a metaheuristic algorithm based on tabu-search is proposed for the solution. The network optimization scheme suggested in this work shows an enhanced coverage granting an *always on* connectivity for vehicle-to-infrastructure networks. Furthermore, due to the optimal number of RSUs, the cost of the network is minimized, which makes the deployment strategy feasible for real scenarios.**

***Keywords*—planning optimization, urban outdoor propagation, VANETs, vehicle-to-infrastructure communication**

I. INTRODUCTION

The number of vehicles is increasing every year and in parallel, the necessity of a reliable communication among them. In vehicular adhoc networks (VANETs) in urban scenarios, the connectivity among vehicles is one of the biggest challenges to face when planning a vehicular network [1]. Due to the high density of buildings and obstacles in these scenarios, the link quality is degraded and, in some occasions, the communication is lost. Therefore, a proper placement of the roadside units (RSU) plays a crucial role. The RSUs are fixed nodes placed close to or along the roads to provide the required connectivity to the vehicular adhoc networks [2]. Since the RSUs are fixed, the transmitted power is much higher than mobile stations, which enables a larger coverage area. Hence, the RSU deployment can be used to create networks based on vehicle-to-infrastructure (V2I) communications, which has been proven to be feasible for non-interactive applications. One of the main applications involving V2I networks is the safety-oriented applications for the vehicles in the network. Thus, an optimal deployment of RSUs to connect all the elements involved in the communication increases the safety level on the roads.

In the recent years, several different approaches for the deployment of the RSUs have been proposed, such as [3], where the deployment is based on placing RSUs in inverse proportion to the expected density of the vehicles, in order to minimize the notification messages. Using a graph representation developed in [4], a scheme is created for placing RSUs using Markov chains to model the traces of the vehicles. These two different approaches study the dynamic nature of the vehicular networks; however, they do not take into consideration the static surrounding environment. Furthermore, the deployment strategy created in [5] aims to maximize the coverage by placing the RSUs in road intersections. A different optimization goal is obtained in [6], where a power-saving model is implemented to reduce the power consumption of active RSUs under a connectivity constraint. The power distribution for each RSU is based on the road-traffic distribution, but it also does not take into consideration the environment scenario as in the previous reviewed studies [3][4]. However, it has been proven in [7], that having a precise knowledge of the particular environment gives a greater accuracy when modeling the propagation parameters. Therefore, using an optimal RSU deployment scheme, based on these propagation parameters, will greatly improve the overall performance and coverage [8] of the vehicular network since disconnected vehicular communications show delays up to 100 seconds, as shown in [9].

In this paper, a novel strategy for the RSU deployment is developed. A particular environment is studied for the deployment of a vehicular network infrastructure, whereby environment-specific details are also taken into account. In order to consider the environment effects, a vehicular radio channel model based on [10] is used to obtain the propagation parameters, combining a deterministic ray-tracing algorithm and a stochastic channel model. Applying this environment-based channel model, along with a context-aware planning algorithm to place the RSUs, an optimized deployment is obtained for a specific area. This planning algorithm maximizes the total coverage of the network while minimizing the number of RSUs. An integer program formulation of the multiobjective optimization problem is presented. Furthermore, a metaheuristic scheme based on tabu-search is proposed for the solution.

The remainder of this paper is organized as follows: Section II describes the environment-based radio channel model used to obtain the radio-wave propagation parameters. Section III analyzes in depth the planning algorithm schemes used for network optimization. In Section IV, the algorithm results are shown and discussed using an exemplary real-world scenario. Finally, concluding remarks are given in Section V.

II. Environment-based Channel Model

The radio channel model, which is used in this section, is site-specific, i.e., the obtained propagation parameters are calculated for a particular scenario. The applied radio channel model is a hybrid approach used in a previous study [11], which combines a deterministic ray-tracing algorithm, PIROPA [12], to obtain the large-scale parameters, and a stochastic model for the small-scale parameters. Placing the transmitter and receivers in the selected environment model, the ray-tracing algorithm predicts the propagation parameters, such as, pathloss, delay, and angle of arrival and departure. Afterwards, using the concept of the *double directional channel* [13], the channel impulse response is calculated as

$$h(t,\tau)=\sum_{n=1}^{N} a_n e^{j\theta_n}\delta(t-\tau_n)\delta(\phi-\phi_n)\delta(\varphi-\varphi_n), \qquad (1)$$

where a_n is the amplitude of the received signal for each ray, δ denotes the Dirac delta function, τ_n is the delay for each ray, θ_n is the phase of the received signal, and ϕ_n, φ_n are the angle of arrival and angle of departure, respectively.

Using this radio channel model, the multipath components of the channel are arranged in clusters, obtaining a complete profile of the channel behavior. The WINNER II channel model is used to simulate the stochastic nature of the radio channel. WINNER II [14] is a geometry-based stochastic model (GBSM) which uses statistical distributions from channel measurements to obtain the parameters. In our approach, the small-scale parameters, such as the phase of the rays within a cluster, the intra-fading in a cluster, cross polarization and fast-fading associated to urban scenarios are computed using WINNER II channel model. Table I shows a summary of the parameters used in the environment-based channel model, as well as, the proposed approach used to calculate it.

TABLE I. Environment-based Channel Model Parameters

Parameter	Symbol	Approach
cluster path power	P_n	PIROPA
cluster AoA, AoD	φ_n, ϕ_n	PIROPA
propagation delay	τ_n	PIROPA
number of clusters	N	PIROPA
per ray AoA, AoD	$\varphi_{n,m}, \phi_{n,m}$	WINNER II
initial phase	$\Phi_{n,m}$	WINNER II
sub clusters delay	$\tau_{n,m}$	WINNER II
cross polarization	$r_{tx,s}, r_{rx,u}$	WINNER II

The channel impulse response of the environment-based channel model $h_{u,s,n}(t,\tau)$ is calculated as a combination of the large-scale parameters, i.e., the parameters which are highly influenced by the environment, from the deterministic ray-tracing algorithm and the small-scale parameters are computed using WINNER II channel model as

$$\begin{aligned} h_{u,s,n}(t,\tau)=\sqrt{\frac{P_n}{N}}\sum_{m=1}^{N}&\sqrt{G_{rx,u}(\varphi_{n,m})}\sqrt{G_{tx,s}(\phi_{n,m})}\\ &\cdot exp(j2\pi\lambda_0^{-1}(\bar{\varphi}_{n,m}.\bar{r}_{rx,u}+\Phi_{n,m}))\\ &\cdot exp(j2\pi\lambda_0^{-1}(\bar{\phi}_{n,m}.\bar{r}_{tx,s}))\\ &\cdot exp(j2\pi\nu_{n,m}t)\delta(\tau-\tau_{n,m}), \end{aligned} \qquad (2)$$

where the parameter P_n is given as

$$P_n=|h(t,\tau)|^2. \qquad (3)$$

As a result, an impulse channel response which combines the advantages of both approaches is obtained in (2). Consequently, the total received power for the environment-based channel model is calculated as

$$P_{TOT}=|h_{u,s,n}(t,\tau)|^2. \qquad (4)$$

The reason to use a hybrid approach for our channel model is that the large-scale parameters are highly dependent on the environment. Thus, the use of site-specific propagation parameters provided by the deterministic ray-tracing algorithm improves the accuracy of the channel model significantly [7]. However, a real scenario is not a static environment, hence, a stochastic variation must be included in the radio channel model. For this reason, the WINNER II channel model is used to obtain the fast variation of the channel which cannot be obtained using the ray-tracing method. In the proposed radio channel model, the central frequency used is 5.9 GHz, which is the predominant frequency for V2I communications [15]. The receiver height is set to 1.5 meters, emulating the size of a vehicle, and the elevation of the RSU has been set to 15 meters.

III. Planning Algorithm

Traditionally, the planning algorithms for urban scenarios, regarding vehicular communications, have been developed without taking into consideration the surrounding scenario [3]-[6]. Using the radio channel model analyzed in Section II, a planning network algorithm is developed exploiting the benefits of the site-specific propagation parameters. In the following, we introduce our notation in the planning algorithm.

TABLE II. Symbol notation

Symbol	Description
$\mathcal{X}=\{x_i\}$	the set of the road points
$\mathcal{R}=\{r_i\}$	the set of possible RSU location
$\mathcal{Z}=\{z_{(i,j)}\}$	the set of possible matchings between $\mathcal{X}$ and $\mathcal{R}$
$\mathbf{y}=\{0,1\}^{n_r\text{x}1}$	optimization variable for the selection of r_i
$\mathbf{z}=\{0,1\}^{n_z\text{x}1}$	optimization variable for the selection of $z_{(i,j)}$
$\mathbf{C}=\{0,1\}^{n_r\text{x}n_x}$	coverage matrix
$C(r_i)=\sum_{j=1}^{n_x}\frac{c_{ij}}{n_x}$	coverage for each potential RSU location
C_{min}	minimal total coverage for optimal solution

We denote the set of possible RSU locations with $\mathcal{R}=\{r_i\}$ and the set of the road points with $\mathcal{X}=\{x_i\}$, where $|\mathcal{R}|=n_r$ and $|\mathcal{X}|=n_x$, where $|\cdot|$ denotes the cardinality of a set. For a test point to be covered by a possible RSU location, we consider the threshold values for received power P_{th}, maximum propagation delay τ_{th}, and the maximum distance to the road point d_{th}. Considering these constraints, we define the coverage matrix $\mathbf{C} = \{0,1\}^{n_r \mathrm{x} n_x}$ with entries c_{ij} as

$$c_{ij} = \begin{cases} 1 & \text{if } x_j \text{ is covered by } r_i, \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

During the execution of the planning algorithm, the RSUs have been configured using the setup parameters in a commercial equipment [16], where the transmitter power is adjusted to 28 dBm. Therefore, using the above mentioned configuration the constraints for the optimization scheme are set as given in Table III.

TABLE III. OPTIMIZATION CONSTRAINT VALUES

Parameter	Value
P_{th}	-95 dBm
τ_{th}	7 μs
d_{th}	100 m

These constraint values are chosen regarding the requirements for a reliable communication and as well as focusing in the priority of low delay communications between the vehicles and the RSUs. This low delay communication scheme is critical for safety-oriented applications and, therefore, it requires to be restrained to a maximal upper bound.

A. Integer Program Formulation

The optimization variable $\mathbf{y}$ for the selection of RSU locations is defined as $\mathbf{y} = \{0,1\}^{n_r \mathrm{x} 1}$, where $y_i = 1$ if r_i is selected for the deployment. Furthermore, we define the set of possible matchings between the possible RSU locations and the road points $\mathcal{Z}$ as

$$\mathcal{Z} = \{z_{(i,j)} = (x_i, r_j) \mid x_i \in \mathcal{X}, r_j \in \mathcal{R}\}, \tag{6}$$

where $|\mathcal{Z}| = n_z$. The optimization variable $\mathbf{z}$ for the selection of a possible matching from $\mathcal{Z}$ is defined as $\mathbf{z} = \{0,1\}^{n_z \mathrm{x} 1}$, where $z_{(i,j)} = 1$ means the assignment of the road point x_i to RSU location y_i. An overview of all the notation is depicted in Table II.

The objective of the network planning problem is to minimize the number of deployed RSUs while maximizing the number of covered points, i.e., the total coverage. This multi-objective optimization problem can be formulated as

$$\text{minimize} \quad \lambda_1 \sum_{i=1}^{n_r} y_i - \lambda_2 \sum_{j=1}^{n_z} z_j \tag{7}$$

$$\text{subject to} \quad \sum_{j, z_{(i,j)} \in \mathcal{Z}} z_{(i,j)} \leq 1 \quad \forall i = 1 \dots n_x, \tag{8}$$

$$z_{(i,j)} \leq y_j \quad \forall z_{(i,j)} \in \mathcal{Z}, \tag{9}$$

$$\mathbf{0} \leq \mathbf{y} \leq \mathbf{1}, \tag{10}$$

$$\mathbf{0} \leq \mathbf{z} \leq \mathbf{1}, \tag{11}$$

where the first term in (7) stands for the number of deployed RSUs, and the second term stands for the number of covered road points. The constraint in (8) ensures the assignment of a road point to at most one RSU, whereas (9) ensures the selection of an RSU location y_j if a road point is assigned to it. The coefficients λ_1 and λ_2 can be selected to achieve a trade-off between the coverage and the number of RSUs. In the present study we set $\lambda_1 = \lambda_2 = 1$. For the optimal solution of this integer linear problem in the present work, we use the commercial optimization solver Gurobi [**?**].

B. Metaheuristic Algorithm

In order to obtain an optimal number of RSUs and their location, a metaheuristic algorithm has been developed. Due to the number of constraints in (8)-(11) involved in the optimization problem and the complexity of the complete problem, a metaheuristic approach gives a good trade-off regarding execution time and optimality of the solution.

Algorithm 1 Algorithm for optimal RSU deployment

Output: $\mathbf{y}$ —vector of selected RSU locations

while $i \leq n_r$ **do**
  if $\sum_{j=1}^{n_x} c_{ij} \geq C_{th} \cdot n_x$ **then**
    $r_i :=$ possible RSU location
  else
    $y_i := 0$ in the solution
  end if
end while

Metaheuristic algorithm:
generate the initial vector $\mathbf{y}_0$ as
while $i \leq n_{\max}$ **do**
  generate $\mathbf{y}_{i+1}$ from $\mathbf{y}_i$
  if $C(\mathbf{y}_{i+1}) \geq C_{min} \cdot n_x$ **then**
    return $\mathbf{y}_{i+1}$
  else
    $i \leftarrow i + 1$
  end if
  if $i > n_{max}$ **then**
    return $\mathbf{y}_i$
  end if
end while

Algorithm 1 shows the flow of the proposed metaheuristic approach, where $\mathbf{y}_0$ denotes the initial vector with all the potential RSU locations, n_{max} is the maximum number of iterations regarding the scenario, and $C_{th} = 1\%$ is the minimal individual coverage for a selected RSU.

The metaheuristic planning algorithm used in this paper is based on tabu-search [17], where the potential RSU locations, which do not cover a sufficient number of points given by C_{th} in per cent, are discarded to avoid unnecessary computations. Due to the complex constraints in the optimization problem, a sub-optimal solution is obtained when the algorithm does not find a feasible optimal solution in the maximum number of iteration n_{max}. The sub-optimal solution gives the best-effort result obtained during the sequential iterations of the algorithm which did not reach the optimal criteria, i.e., the total coverage does not fulfill the given requirement C_{min}.

The metaheuristic algorithm consists of obtaining the individual local maximums of coverage for each RSU, using a greedy strategy. Subsequently, the total coverage obtained with the selected RSU formation is evaluated, i.e., whether the total coverage fulfills the constraints, $C(\mathbf{y}_{i+1}) \geq C_{min} \cdot n_x$. If this constraint is fulfilled, the RSU formation is valid. Hence, the algorithm pursuits a double optimization goal:

(i) maximization of the total coverage for the selected RSU set, and
(ii) minimization of the number of RSUs to obtain an optimal RSU deployment, regarding the network cost.

Therefore, the general idea for the algorithm is denoted as follows

$$\max_{\mathbf{y}\in\{0,1\}^{n_r \text{x} 1}} C(\mathbf{y}). \tag{12}$$

IV. Performance Evaluation

In this section, the entire procedure of network planning is described on a real scenario, and the execution performance of the optimization algorithm is analyzed in depth.

A. Map Extraction

The studied scenario is obtained using OpenStreetMaps [18], including the building and road data. The scenario data is required to obtain the propagation parameters using the radio channel model developed in Section II, and to execute the network planning algorithm from Section III.

Fig. 1. Image of the analyzed area in Cologne, Germany

The selected area is an urban environment with a high density of buildings and roads, as shown in Fig. 1. The area which is located in Cologne, Germany, is approximately of 5 km^2. The average height of the buildings is four floors and the roads are classified as urban, i.e., the maximum speed is 50 km/h. Therefore, this scenario is exemplary for most of the territory in Germany, where the distribution of roads and buildings is similar to the one displayed in Fig. 1. The details of the considered scenario are summarized in Table IV along with the number of possible RSU locations n_r and the number of road points n_x.

TABLE IV. Details of the considered scenario

Parameter	Value
Area	5 km^2
n_r	21
n_x	1857

B. Road Network Extraction

Once the complete information from the studied area is obtained, the road points have to be extracted for analysis. Using the data format from OpenStreetMaps, the road network is defined as a relation between map nodes, similar to a graph form. However, the geographical distance between the nodes is occasionally too high. Therefore, intermediate nodes have to be added to obtain enough granularity to simulate a realistic scenario. The newly added nodes are interpolated between the existing ones, approximately every 1 meter, creating an almost uniform distribution of the road points.

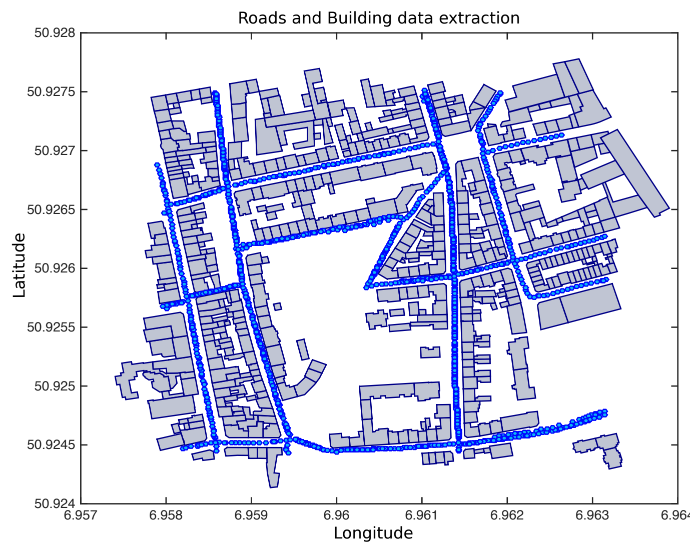

Fig. 2. Extracted road points and building data from the selected area

The result from the roads extraction is shown in Fig. 2, where some areas have a higher concentration of points due to the architecture of the road network. In this step of the execution, it is worth mentioning the importance of the context-aware approach for the deployment of the RSUs. Having the information of the scenario, it is possible to allocate a higher number of network resources, i.e., RSUs, to a specific area with a higher expected number of users.

C. Potential RSU Locations

The expected locations of the RSUs are the road intersections, where a higher concentration of road points are located. This assumption is logical from the point of view of maximizing the local coverage of each RSU, and moreover, it will cover a conflictive point for traffic safety as crossings. This is an additional advantage, because the closer the RSUs are to the affected traffic zone, e.g., by a collision, traffic jam, etc., the lower the notification time to the rest of the network will be.

The potential RSU locations are distributed accordingly to the concentration of road points. Since an RSU cannot

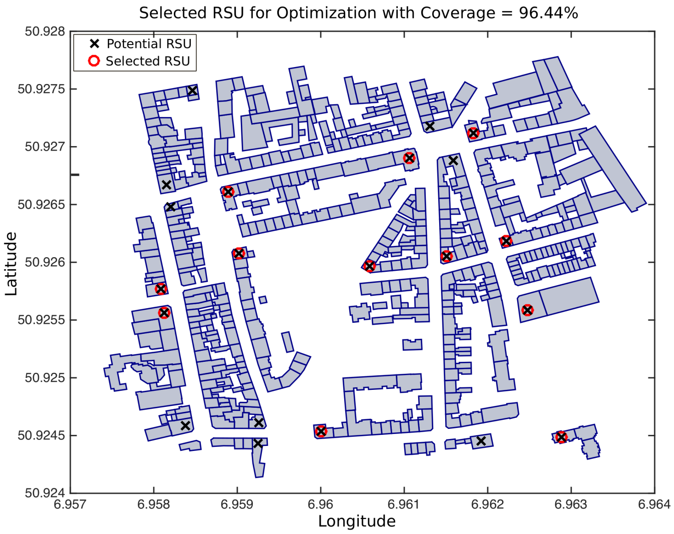

Fig. 3. Potential and selected RSUs

be located on the road, the strategy to place the RSUs is the following: the coordinates of the road crossing are obtained, and considering that the building data of the scenario is available, the centroid of the closest building to place the RSU is calculated. Since the scenario is urban, the RSU will be placed on top of the buildings, having an average height of 40-50 meters. It is noteworthy that the potential RSUs are not uniformly distributed, as is expected for a context-aware deployment where the particular architecture of the scenario is fundamental, as shown in Fig. 3.

D. Selected RSU Locations

After executing the optimization algorithm fulfilling the double optimization goal, i.e., maximum coverage and minimum number of RSUs, the selected RSU formation is obtained. The selected RSU formation for the specific studied scenario is shown in Fig. 3. Using the selected formation from the metaheuristic method, the achieved total coverage is 96.44 %, close to the complete coverage of the specific area. In case an optimal solution cannot be achieved in the required number of iterations, the sub-optimal RSU formation will be generated. It is noteworthy, that in occasions due to the particular geography of the scenario, a total coverage of the network is not possible. Therefore, adding auxiliary RSUs to reach these isolated road points would be a practical solution.

E. Planning Strategy Analysis

In this section, an analysis of the planning strategy is realized. First of all, a traditional uniform non-context aware RSU deployment is specified as a comparative reference. The number of RSUs for total coverage using an uniform planning $n_{r,\text{uniform}}$ is as follows:

$$n_{r,\text{uniform}} = \frac{S_T}{S_i} = \frac{800 \times 600}{\pi(100)^2} = 15 \tag{13}$$

where S_T is the total area surface of the scenario, and S_i is the maximum area covered by each individual RSU. The calculated value in (13) is inferior to the one obtained in the approach used in this paper, as shown in Fig. 3. However, the uniform value is calculated without taking into account the surrounding scenario, i.e., not considering the variations in the radiowave propagation parameters created by the environment. In our approach, a more realistic model is used, considering the scenario buildings and obtaining the propagation parameters according to them.

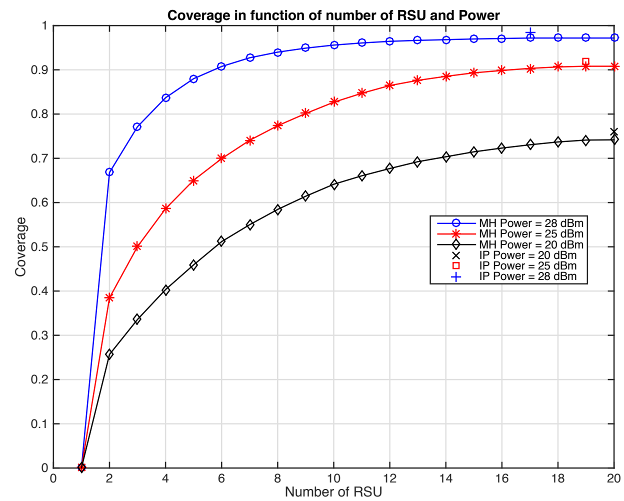

Fig. 4. Selected RSU formation to maximize the network coverage

In Fig. 4, the evolution of the planning algorithm is presented. It shows the increment of total coverage as function of the number of allocated RSUs. The graphs obtained using the metaheuristic algorithm have an upper bound given by the environment, i.e., the maximum coverage due to the particular geography of the scenario. However, using the integer program formulation approach, we obtain the optimal point regarding coverage and number of RSUs. It is interesting to remark that the contribution to the network by each RSU, i.e., the unique road points reached by the RSU, decreases when the number of RSU increases. This is consistent with our approach, since we do not take into consideration the overlapping points for our algorithm, and the higher the number of chosen RSUs is, the higher the probability of overlapping.

V. Conclusion

In this paper, a novel planning algorithm for vehicular networks has been proposed. The most important characteristic of the planning algorithm is its context-awareness, which enables to optimize the RSU deployment in a specific given scenario. This approach has the advantage of exploiting the characteristics of the environment and using them to obtain a more reliable and fully connected network.

The scenario behavior is added to the planning algorithm using an environment-based channel model. The applied state-of-the-art radio channel model combines the characteristics of a ray-tracing algorithm along with the flexibility of a stochastic approach provided by the WINNER II channel model.

Once the propagation parameters are obtained for the environment-based channel model, a metaheuristic planning algorithm, based on tabu-search, uses these parameters to obtain the optimal RSU formation for the given scenario. The algorithm selects the RSU with a higher individual coverage while discards the ones which contribute below a certain fixed level. The resulting RSU formation is optimized for the given scenario and assures a high coverage rate for the scenario. Moreover, an integer formulation is developed obtaining the optimal number of RSUs while maximizing the coverage for the selected set of RSUs.

Using the proposed planning algorithm, coverage in urban areas can be greatly improved and therefore its reliability, obtaining a network architecture where the traffic-safety applications would perform perfectly.

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