Location-Based Scheduling for Cellular V2V Systems in Highway Scenarios

Richard Fritzsche, Andreas Festag
Fraunhofer Institute for Transportation and Infrastructure Systems IVI, Dresden, Germany
Email: {richard.fritzsche, andreas.festag}@ivi.fraunhover.de

***Abstract*—In intelligent transport systems (ITS), vehicular users broadcast messages with ego information such as position, speed, and other. For exchanging ITS messages directly among vehicles via cellular sidelink transmission, the base station assigns dedicated V2V radio resources for users in coverage. To improve spectral efficiency, the same radio resource can be simultaneously scheduled to multiple vehicles within a cell, e.g., based on a minimum vehicle distance. This distance can be determined by location information obtained from ITS messages.**

In this work, we introduce a framework for location-based scheduling, exposing basic relations among cell spectral efficiency, communication range and reliability. Based on the framework we show that an optimal scheduling distance exists, which maximizes the cell throughput by guaranteeing range and reliability constraints. The optimized distance can then be utilized by the base station scheduler, which benefits from a closed form solution for the outage probability, derived in this work. We validate that the proposed form with its simplifications achieves a similar performance compared with the optimal solution, obtained by Monte Carlo simulations.

I. INTRODUCTION

Intelligent transport systems (ITS) have been subject of research for several decades. In this area, direct vehicle-to-vehicle (V2V) communication has received a lot of attention in recent years [1]. While early applications focused on driver information and warning, in the context of road safety and traffic efficiency [2], more advanced use cases are subject of current studies. A major impact is also given by the interest in autonomous driving, for which vehicular communication is regarded as a key enabler technology to ensure safety requirements by enhancing pure sensor-based vehicle perception [3].

While IEEE 802.11 OCB (outside the context of a basic service set) based systems are ready to market, recent 3GPP standardization activities present cellular V2X (vehicle-to-everything) as a proper technological alternative [4]. Both technologies have several commonalities but also substantial differences. One aspect is that 802.11 OCB is solely based on random access, while cellular V2X benefits from the possibility of resource scheduling for in-coverage users, typically resulting in higher spectral efficiency [5]. For scheduling, a pool of dedicated time-frequency radio resources is used for V2V communication via sidelink [6]. Sidelink transmissions are based on broadcast, where messages can be decoded by any device experiencing an appropriate signal-to-interference-plus-noise ratio (SINR). Especially under line-of-sight conditions, the signal strength significantly depends on the distance between transmitter and receiver.

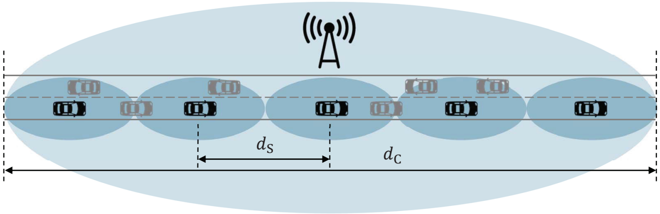

Fig. 1. Cellular V2V communications in a one-dimensional highway scenario exploiting location-based resources scheduling. Vehicular users transmitting on the same radio resource are separated by the minimum scheduling distance d_S and are "packed" within the cell of range d_C.

In principle, the *communication range* defines the maximum distance at which a message can be successfully decoded with a desired probability. The latter reliability figure is typically quantified by *outage probability*. In practice, concrete values for communication range and outage probability are determined by specific service requirements, e.g., of ITS applications. From the receiver perspective, both parameters not only depend on the range to the message origin, but also on the distance to surrounding interferers transmitting on the same radio resource. As a consequence, it seems plausible to re-schedule resources for vehicles based on their locations [7].

For out-of-coverage communication, where no base station (BS) is available, vehicles in *unmanaged mode* independently select transmission resources based on channel sensing and semi-persistent scheduling indicators [8], [9] (mode 4 in LTE release 14 [4]). In this work, we focus on in-coverage users in *managed mode* (mode 3 in LTE release 14), where resources for sidelink communication are assigned by the BS. Assuming requirements on communication range and outage probability, the BS can assign the same radio resources to multiple vehicular transmitters separated by a minimum distance (referred to as *scheduling distance*). Following this approach, there is a certain number of transmitting vehicles per resource which "fit" into a mobile radio cell. This concept is illustrated in Fig. 1 for a one-dimensional highway scenario with *cell range* d_C and scheduling distance d_S. For the described relations we present a mathematical framework on location-based scheduling and show that there is an optimal d_S, which maximizes the cell spectral efficiency by ensuring constraints on communication range and reliability. Based on our framework, we derive a closed form expression on outage probability considering highway scenarios with the two closest interferers.

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Related work on resource sharing for sidelink has been presented in [10], considering different system assumptions, e.g., channel knowledge at the transmitter. In [11] location information is used for zoning in mode 4 (static areas assigned with dedicated resource pools). Even though the assumptions differ from our work (dynamically scheduled resources for vehicles in mode 3), there are similarities in the underlying framework. A vehicle clustering concept for offloading based on sidelink is presented in [12].

The remainder of this paper is structured as follows. The system model is presented in Section II before the mathematical framework together with scheduling optimization are introduced in Section III. Section IV examines the derivation of the closed form solution for the outage probability, while Section V shows performance results followed by conclusions in Section VI.

II. SYSTEM MODEL

In this section we introduce assumptions of the underlying system model and show some fundamental relations among parameters, which are of interest for our framework presented in Section III. The radio channel between transmitter and receiver is commonly modeled considering two main effects: *slow fading* due to path loss and shadowing as well as *fast fading* caused by multi-path propagation and movements of the vehicular users. For a specific link i we define the Gaussian distributed channel coefficient

$$h_i \sim \mathcal{CN}\left(0, \lambda_i\right), \tag{1}$$

whose mean channel gain reflects slow fading effects and can be defined as

$$\lambda_i = \beta d_i^{-\alpha} \tag{2}$$

with distance d_i, path loss exponent α and the shadow fading coefficient β. The two latter parameters adjust the model to particular environmental conditions [13]. With the complex amplitude of the fading channel (1), its power is given by $g_i = ||h_i||^2$ and follows a Chi-squared distribution [14]:

$$f_{g_i}(x) = \begin{cases} \frac{1}{\lambda_i} \exp\left(-\frac{x}{\lambda_i}\right) & x \geq 0 \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

In general, we assume that K interfering users transmit on the same radio resource as the source node, each with power ρ_i. With the source transmit power ρ_0 and the receiver noise power σ_n^2 the capacity of the block static channel is

$$C = \log_2\left(1 + \frac{\rho_0 g_0}{\sigma_n^2 + \sum_{k=1}^{K} \rho_k g_k}\right), \tag{4}$$

and refers to the maximum number of bits that can be transmitted per channel use (time-frequency element of an OFDM system). We assume that the interferers' channels are not known at the receiver, since there is no dedicated scheduling of reference signal resources. Consequently, successive interference cancellation cannot be applied at the receiver and the interfering signals need to be treated as noise.

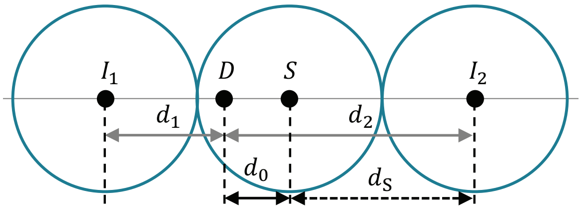

Fig. 2. Geometry and distances for the one-dimensional highway scenario with message source S, destination D and two interferers I_1 and I_2.

Since V2V communication is based on broadcasting, an alignment of the transmitter to the instantaneous channel state is not possible. Therefore, predefined settings for transmit power as well as modulation and coding scheme are applied. Depending on the channel conditions between source and receive node, the transmitted block can either be decoded or not. More specifically, if the transmission rate R does not exceed the channel capacity (4), the block is decodable. Otherwise, the block cannot be decoded. Note that hybrid automatic repeat request is not suitable without feedback channel. Based on the assumptions above, an essential metric of our framework is given by the outage probability

$$p = \mathbb{P}\left(\log_2\left(1 + \frac{\rho_0 g_0}{\sigma_n^2 + \sum_{k=1}^{K} \rho_k g_k}\right) < R\right). \tag{5}$$

The probability operator $\mathbb{P}$ in (5) is w.r.t. the random channel gains g_i, with $i = 0, ..., K$. The random term in (5) corresponds to the received SINR ϑ, which allows to write

$$\begin{aligned} p &= \mathbb{P}\left(\log_2\left(1+\vartheta\right) < R\right) \\ &= \mathbb{P}\left(\vartheta < 2^R - 1\right) \\ &= \mathcal{F}_\vartheta\left(2^R - 1\right). \end{aligned} \tag{6}$$

From (6) we observe that the outage probability can be obtained by evaluating the cumulative distribution function (CDF) of the SINR ϑ at point $2^R - 1$. In order to do so, we first need to find the SINRs probability density function (PDF) $f_\vartheta(x)$.

III. FRAMEWORK AND OPTIMIZATION

The definitions in Section II are utilized for the framework we present in this section. On that basis we can optimize the scheduling distance for a target outage probability together with a desired communication range. For clarity of presentation we refer to a one-dimensional highway scenario with two interferers, even though the framework is not restricted to that. Differences to a more general scenario will be stated if required.

We assume vehicular communications among users arranged along a straight road section, as illustrated in Fig. 2. On the horizontal line (which corresponds to the road section), four vehicles are located, denoted by S, D, I_1 and I_2, referring to source, destination and the two closest interferers, respectively. Node S broadcasts a message which is of interest for destination node D. The distance between both nodes is denoted by d_0. The radio resource, utilized by S is also occupied by the two interferers I_1 and I_2 for broadcasting their own messages. We assume that the useful signal of S as well as unwanted signals of I_1 and I_2 are received at D, while the interference might disturb the successful decoding of the message. The received strength of the harmful signal depends on the distances between destination and each interferer, indicated as d_1 and d_2. The distance between source and each interfering node is denoted by the scheduling distance d_S. Note that d_S is the minimum distance of two vehicular users transmitting at the same resource block.

From (5) and (6) we conclude, that the PDF f_p shows the relation between outage probability p and the transmission rate R. Furthermore, we observe from (5) and by incorporating (2), that p depends on the communication rage d_0 (the distance between source and destination) as well as on the distances between interferers and destination d_i, with $i = 1, ..., K$. From Fig. 2, we exemplarily observe that $d_1 = d_S \mp d_0$ and $d_2 = d_S \pm d_0$. As a consequence we can formulate the outage probability as

$$p = f_p(R, d_0, d_S). \tag{7}$$

Equation (7) tells us that a receiver with distance d_0 from the transmitter can decode the transmitters' message with probability p if it was sent with rate R and the interferers are separated by d_S from the transmitter. More specifically, if the receiver is within communication range d_0 from the transmitter, the message can be decoded with at least probability p. Note that f_p also depends on the transmit power and the receiver noise power, which are assumed to be fixed in this work.

In order to determine the necessary transmission rate R for given parameters p, d_0 and d_S, we are interested in the inverse function of (7):

$$R = f_p^{-1}(p, d_0, d_S). \tag{8}$$

With the transmission rate in (8) and the outage probability we can formulate the average number of bits per channel use, that are successfully decodable at the receiving vehicle. This term is denoted as throughput per radio resource or more commonly as spectral efficiency

$$T = (1-p) f_p^{-1}(p, d_0, d_S). \tag{9}$$

Note that the optimization of p in (9) is not subject of this work, since practical systems typically guarantee a fixed target outage probability.

We illustrated in Fig. 1 that for a cell range d_C, a particular number of users (utilizing the same radio resource) can be "packed" into the cell, by allowing those users to be separated by distance d_S. For the considered one-dimensional scenario, in which the road exploits the full cell range, the number of users results in d_C/d_S. Note that we do not restrict ourselves to an integer number of users, in order to preserve the general applicability of the result. We remark that for a two-dimensional scenario the number of users per cell is different.

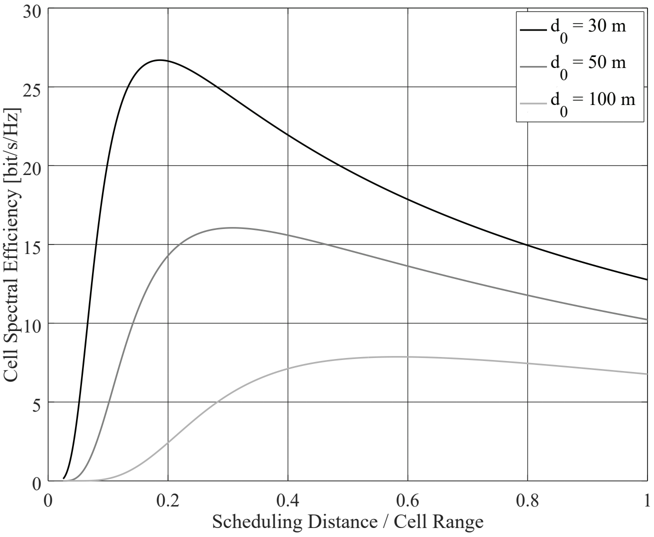

Fig. 3. Exemplary illustration of the optimization problem for a target outage probability $p = 0.01$ at different communication ranges d_0 assuming two interferers. The graphs are obtained by Monte Carlo simulations.

With the previous considerations, we can now formulate the cell spectral efficiency to

$$T_C = \frac{(1-p)d_C}{d_S} f_p^{-1}(p, d_0, d_S). \tag{10}$$

The behavior of (10) w.r.t. the scheduling distance d_S is exemplarily illustrated in Fig. 3 for a setup with two interferers, which is generated based on Monte Carlo Simulations over the random fast fading coefficients h_i, with $i = 1, 2, 3$. It can be observed that the cell spectral efficiency is a quasi-concave function of the scheduling distance d_S and therefore has only a single maximum. We can now write down the optimization problem as

$$d_S^\star = \arg\max_{d_S} \ \frac{(1-p)d_C}{d_S} f_p^{-1}(p, d_0, d_S). \tag{11}$$

Due to the quasi-concavity, standard methods can be applied to find the maximum, e.g., Newton's method [15]. By inserting $d_S^\star$ into (8) we obtain the optimal transmission rate $R^\star$. Note that the scheduling itself is performed per transmission block, while the adjustment of the scheduling distance might change on a much lower frequency, according to variations in service requirements or vehicular dynamics.

Summarizing this section, we define the basic algorithm steps:

1) Determine required target communication range d_0 and the outage probability p
2) Calculate the optimal scheduling distance $d_S^\star$ from (11), by, e.g., Newton's method
3) Assign the transmission rate $R^\star$ obtained from (8) to each vehicle

However, at this point we neither have a closed form expression of f_p nor of f_p^{-1}. This problem is subject of the following section. If f_p and f_p^{-1} cannot be derived analytically, simulation based lookup tables can be used.

IV. DERIVATION OF OUTAGE PROBABILITY

In this section we describe the derivation of outage probability for the one-dimensional scenario, as introduced in Section II. We assume that the two closest interferers are sufficient for describing the SINR in a proper way. We further assume that vehicles transmit with the maximum allowed power ρ. With $\eta = \sigma_n^2/\rho$, the SINR at the destination simplifies to

$$\vartheta = \frac{g_0}{\eta + g_1 + g_2}. \tag{12}$$

Considering (6) we are interested in finding the PDF of the SINR ϑ in order to derive the outage probability for a specific source-destination setup. With (3) we already know the channel gain distribution of each link i.

In a first step, we gather the two interfering channel gains in (12) to a single random variable $\bar{g} = g_1 + g_2$. The PDF of $\bar{g}$ can be obtained from stochastic calculus and writes as follows

$$\begin{aligned} f_{\bar{g}}(x) &= f_{g_1} * f_{g_2}(x) \\ &= \frac{1}{\lambda_1 \lambda_2} \int_{-\infty}^{\infty} \exp\left(-\frac{t}{\lambda_1}\right) \exp\left(-\frac{x-t}{\lambda_2}\right) dt. \end{aligned} \tag{13}$$

Since the PDF of g_i is zero for $x < 0$, the integration limits in (13) are adjusted to

$$\begin{aligned} f_{\bar{g}}(x) &= \frac{\exp\left(-\frac{x}{\lambda_2}\right)}{\lambda_1 \lambda_2} \int_0^x \exp\left(t\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)\right) dt \\ &= \frac{\exp\left(-\frac{x}{\lambda_2}\right)}{\lambda_1 - \lambda_2} \left[\exp\left(x\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)\right) - 1\right] \\ &= \frac{1}{\lambda_1 - \lambda_2}\left(\exp\left(-\frac{x}{\lambda_1}\right) - \exp\left(-\frac{x}{\lambda_2}\right)\right), \end{aligned} \tag{14}$$

which relates to the interference experienced at the destination node. In the second step, we include the constant η and define $\tilde{g} = \eta + \bar{g}$. The result is a shift of the PDF in x direction:

$$f_{\tilde{g}}(x) = \begin{cases} \frac{1}{\lambda_1 - \lambda_2}\left(\exp\left(\frac{\eta - x}{\lambda_1}\right) - \exp\left(\frac{\eta - x}{\lambda_2}\right)\right) & x \geq \eta \\ 0 & \text{otherwise.} \end{cases} \tag{15}$$

In the final step, the PDF of the complete SINR term $\vartheta = g_0/\tilde{g}$ is derived. With $f_{g_1/g_2}(x) = \int_{-\infty}^{\infty} |t| f_{g_1}(xt) f_{g_2}(t) dt$ we write

$$\begin{aligned} f_\vartheta(x) =& \frac{1}{\bar{\lambda}} \int_\eta^\infty t \exp\left(-\frac{xt}{\lambda_0}\right) \cdot ... \\ & ... \cdot \left(\exp\left(\frac{\eta - t}{\lambda_1}\right) - \exp\left(\frac{\eta - t}{\lambda_2}\right)\right) dt, \end{aligned} \tag{16}$$

where the additional parameter $\bar{\lambda} = \lambda_0(\lambda_1 - \lambda_2)$ is introduced to ease readability. Consulting the general solution of the indefinite integral

$$\int x \exp(cx)\, dx = \exp(cx) \left(\frac{cx - 1}{c^2}\right), \tag{17}$$

we can solve (16) and obtain a closed form for the PDF of the SINR, which reads

$$f_\vartheta(x) = \frac{\eta^2}{\bar{\lambda}} \exp(-\eta_0 x) \left[\frac{\eta_0 x + \eta_1 + 1}{(\eta_0 x + \eta_1)^2} + \frac{\eta_0 x + \eta_2 + 1}{(\eta_0 x + \eta_2)^2}\right] \tag{18}$$

with the link specific coefficients $\eta_i = \eta/\lambda_i$. Based on the result in (18) we can now calculate the CDF of ϑ at the point $b = 2^R - 1$ as initially required for solving (6). Therefore, we write

$$\begin{aligned} p &= \int_0^b f_\vartheta(x) dx \\ &= \frac{\eta^2}{\bar{\lambda}} \int_0^b \exp(-\eta_0 x) \cdot ... \\ & \quad ... \cdot \left[\frac{\eta_0 x + \eta_1 + 1}{(\eta_0 x + \eta_1)^2} + \frac{\eta_0 x + \eta_2 + 1}{(\eta_0 x + \eta_2)^2}\right] dx. \end{aligned} \tag{19}$$

With the chain rule, we can formulate the general integral solution

$$\begin{aligned} & \int_0^b \exp(-\eta_0 x) \frac{\eta_0 x + \eta_1 + 1}{(\eta_0 x + \eta_1)^2} dx = ... \\ & \quad ... = \frac{1}{\eta_0} \left(\frac{1}{\eta_1} - \frac{\exp(-\eta_0 b)}{\eta_0 b + \eta_1}\right). \end{aligned} \tag{20}$$

Now the final step for the general two interferers solution can be done by applying the general integral in (20) for solving equation (19). As a result, we obtain a closed form expression for the outage probability

$$p = 1 - \exp\left(\frac{-\eta b}{\lambda_0}\right) \left[\frac{b^2 \lambda_1 \lambda_2}{\lambda_0^2} + \frac{b(\lambda_1 + \lambda_2)}{\lambda_0} + 1\right]^{-1}. \tag{21}$$

Note that the expression in (21) corresponds to a general arrangement comprising the source-destination link λ_0 and the two closest interferers with their mean channel gain λ_1 and λ_2, respectively.

With reference to the straight road section scenario, where all users are located on a single line as illustrated in Fig. 2, we can further elaborate on (21). We utilize (2) and include the distances as discussed in Section II, by replacing $d_1 = d_S \mp d_0$ and $d_2 = d_S \pm d_0$. Furthermore, we introduce the parameter $\gamma_R = \beta d_R^{-\alpha} \rho / \sigma_n^2$, which describes the target SNR experienced at a reference distance d_R to the source node. The parameter γ_R is for ease of readability and is chosen according to the allowed transmit power and the required receiver sensitivity. With these assumptions, we are able to obtain the outage probability in (22).

$$p = 1 - \exp\left(\frac{1 - 2^R}{\gamma_R} \left(\frac{d_R}{d_0}\right)^{-\alpha}\right) \left[(2^R - 1)^2 \left(\left(\frac{d_S}{d_0}\right)^2 - 1\right)^{-\alpha} + (2^R - 1)\left(\left(\frac{d_S}{d_0} + 1\right)^{-\alpha} + \left(\frac{d_S}{d_0} - 1\right)^{-\alpha}\right) + 1\right]^{-1} \tag{22}$$

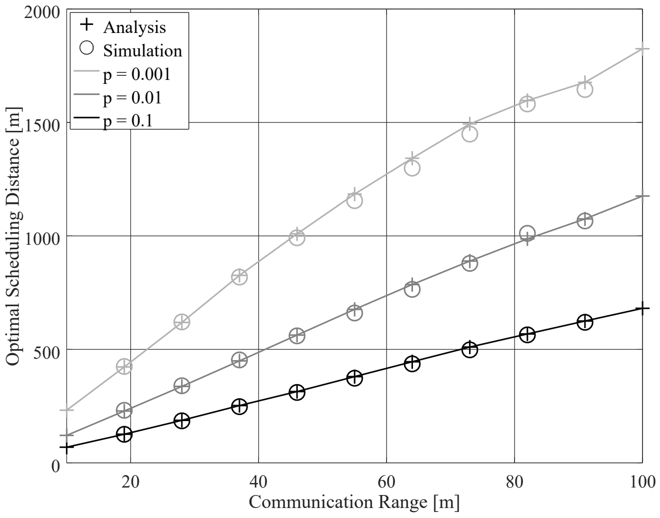

Fig. 4. The optimized scheduling distance as a function of the target communication range for different outage probabilities p

V. PERFORMANCE EVALUATION

We now apply the formerly presented findings and show the accuracy of our proposed solution compared to simulations, which take more interferers into account. We use the parameters $\alpha = -3.5$ and $\beta = 144.5\,\text{dB}$ for adjusting the channel model. Furthermore, the experienced SNR at the cell edge $d_C/2 = 1\,\text{km}$ is $\gamma_R = 10\,\text{dB}$. We utilize the outage probability results derived in Section IV and incorporate them into the algorithm presented in Section III. For finding the inverse function in (8) software solvers (or in practical systems look-up tables) are used. Note that, although we do not have a direct solution for the inverse function, we still obtain an efficient algorithm with tremendous complexity reduction compared to Monte Carlo simulations.

Fig. 4 shows results on the optimized scheduling distance as a function of the communication range for different target outage probabilities. It can be observed that for achieving a communication range of $d_0 = 100\,\text{m}$ with reliability $p = 0.001$ only a single user can be scheduled per cell resource. However, practical scenarios are assumed to have less restrict requirements and substantial performance gains in terms of cell throughput are expected by location based scheduling. Note that in a two-dimensional case, the expected performance gain increases, since a higher number of users "fit" into cell compared to a single line assumption.

In addition, we compared the solution based on the analytical expression with Monte Carlo simulations including more than two interferers (cycles in Fig. 4). We observe that the accuracy of our proposed analytical solution ('+'-marks in Fig. 4) performs close to the optimum. The fluctuations in both analytical results and simulations are due to a finite number of values for the scheduling distance and the transmission rate, which is needed to obtain values for (8) and (3).

VI. CONCLUSIONS

In this work, we presented a framework for location-based scheduling for the in-coverage mode of a cellular V2V system. We explored relations among cell throughput, reliability and communication range, from which we showed that an optimal scheduling distance exists. For a one-dimensional highway scenario considering the two closest interferers we derived a closed form solution for the outage probability. This form allows us to find the optimal scheduling distance by a simple algorithm, without performing Monte Carlo simulations. We validated that the proposed solution has similar accuracy compared to simulations including more interferers. The presented framework is the basis for future studies on two-dimensional scenarios, implying larger complexity but also guaranteeing better applicability.

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