Virtual Source Modeling for Diffraction in Reference Channel Models

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***Abstract*—The paper investigates diffraction-specific ray properties which should be implemented in reference channel models in order to achieve physically correct representation of diffraction. When modeling propagation by diffraction (mostly in urban settings), one needs to decide on how to arrange virtual sources of rays that arrive from the base station to the user. Usually, virtual sources are placed at the edges of buildings where diffraction occurs. The paper analyses if this usual approach is appropriate, especially in the case of mobile users, where Doppler frequency shift needs to be modeled correctly. To that goal, a model for virtual source is established, that mimics correctly angles of arrival, time delay and Doppler frequency shifts.**

***Index Terms*—diffraction; urban scenario; virtual source; Doppler frequency shift; MIMO**

I. Introduction

Last decade has seen a lot of research in development of adequate tools for verification and performance comparison of new wireless systems, their protocols, antenna (MIMO) concepts, coding schemes and modulations, frequency allocations, signal masks etc. The main purpose of these tools is to simulate radio channels and serve as a reference for system comparison, so they are commonly referred to as Reference Channel Models (RCM).

Although RCMs do not need to resemble any specific field trial, they do need to be realistic and mimic meaningful multipath propagation environments. They are thus based either on sets of comprehensive measurements, or on ray tracing simulated scenarios, which are processed and usually used for model parameterization.

Most of RCMs are stochastically based and known as *Geometry-based Stochastic Channel Models* (GSCM) [1,2]. The prominent representatives in the GSCM family are COST 259 and COST 273 models [3]-[5], as well as their latest counterpart, COST 2100 model [6,7]. Their mode of operation is in mimicking the realistic multipath environment by applying laws of propagation on randomly (stochastically) chosen specific parameters (Tx, Rx and obstacles) extracted from measurements or ray-tracing simulations. In other words, GSCMs are controlled by stochastic parameters, so, due to the random nature of their creation, stochastic channel model realizations may turn out to be unrealistic.

An alternative approach of Deterministic Reference Channel Model (DRCM) is proposed in [8].This model would directly encompass exclusively measured or ray-tracing analyzed channels from real world geometries that are currently used only for feeding stochastic channel models before parameterization, thus omitting the parameterization process and uncertainty of model outcomes. It would enable direct testing of communication systems on real channels, obtained either by ray-tracing or measurements.

In either case, whether it is stochastically based model or DRCM, it is necessary to implement all propagation phenomena. In the first place, this includes different propagation modes (i.e. direct rays, refraction, diffuse scattering, reflection and diffraction) and their geometry properties, which need to be well described in both static and mobile user case.

This paper aims at giving guidelines for the implementation of diffraction in RCMs in urban radio channels, especially in the respect of mobile users. Virtual sources for propagation by diffraction are observed to move rapidly in urban setting [9,10], which motivated our research into reasons behind it and consequences for RCMs. In case of diffraction, the movement of interaction point is synchronized with the movement of mobile unit, raising a question of necessity for a new form or paradigm for modeling Doppler effect and diffracted ray source position. Similar problem, but for satellite-to-earth (indoor) links and for multiple-bounces reflections, has been addressed in [11].

II. Diffraction in Urban Environment

Diffraction is significant, if not dominant mode of propagation in urban scenarios [9], which creates, due to the large number and high density of scatterers (i.e. buildings), a rich and very dynamic multipath environment.

In case of diffraction, the virtual source may be considered to lie on the vertical corner edges of buildings – diffraction interaction points (DIPs), but unlike the reflection case where the virtual source location is fixed, here the virtual source may slide along the edge (i.e. corner of the building), as the user location moves. This is due to the Keller's cone condition [12, 13] as depicted in Fig. 1. For the same impinging wave, depending on the orientation of the user route to the cone, one could observe the drifting of the DIP (e.g. in points A, B, D along the route in Fig. 1) or static DIP (in the vicinity of point C where the route in Fig. 1 is tangential to the Keller's cone).

In 3D ray-tracing simulations, the diffraction point is usually set in the middle of the (building) edge where the diffraction occurred [14, 15]. Its position is corrected later on, after ray-tracing reaches the final point or the user. The complete Tx-Rx path can then be backtracked and DIPs shifted as appropriate.

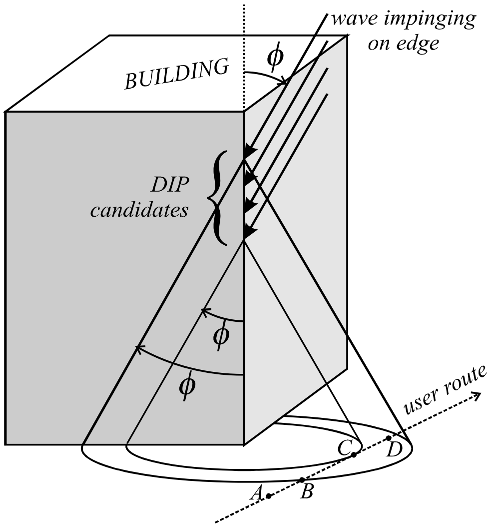

Figure 1 - Rays diffracted on vertical edge diffract along a cone; semi-angle ϕ equals to angle of incidence on the edge.

III. MODELING DOPPLER FREQUENCY SHIFT AND VIRTUAL SOURCE LOCATION

From observations in Section II it is obvious that for the modeling of user mobility in diffraction environment, it is necessary to understand location and movement of ray's virtual sources (VS) that are correlated with the movement of the user. In this paper only single diffraction is considered, but generalization of findings for multiple diffractions, possibly combined with reflections, is straightforward.

Natural choice for virtual source is a point in ray’s direction of arrival (DoA), as seen by the user, at a distance corresponding to the total path length from base station to the user, which represents a location from where the identical ray would depart towards the user, in case of unobstructed environment. However, DIP is also located in the same direction of arrival (albeit at the diffracting edge), so the question is: can DIP also be used as a VS, at least for the calculation of Doppler shift (since time delay is surely different), and how does the movement (i.e. sliding) of DIP influence the overall Doppler shift.

It will be shown, that it is appropriate to set VS exclusively at location that, from delay and angle points of view, appears as a source to the mobile user. Therefore this point will already be labeled as VS in forthcoming figures. The other alternative location, DIP, yields different and incorrect Doppler shift, as it will be shown.

For derivation it is needed to separate two, mutually orthogonal pivotal cases of user movement as Fig. 2 shows, one directed towards the edge of the building (a), and the other circling around the edge (b). These movement directions are orthogonal, thus their linear combination can represent any user movement. Fig.2a) shows how, during radial movement towards the DIP, VS is static, whereas DIP is sliding. Fig.2 b) shows how, during circling around DIP, VS is circling also with same angular speed and DIP is static. Obviously, in case a) Doppler frequency shift is highest, and in case b) it is zero.

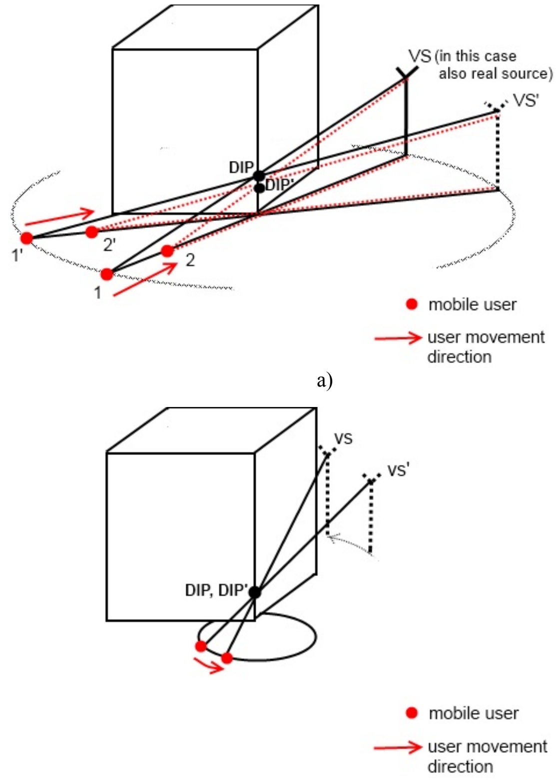

Figure 2 - Two orthogonal movements with their specific impact on location of DIPs and VSs. In a) it is shown that except for the azimuth angle of arrival, geometry of rays when user is moving from 1 to 2, or from 1' to 2' is identical

Note that when Doppler shift is the highest (radial movement of user towards the edge), the VS is stationary and DIP slides (Fig. 2 a)), whereas when user movement is rotation around the diffraction edge axis, VS is moving (albeit rotating with same angular velocity as the user), and DIP is fixed (Fig. 2 b)).

Doppler frequency shift can be calculated as:

$$f_d = f_0 \frac{v_0}{c} \tag{1}$$

where v_0 is relative velocity of user and source (base station) towards each other, f_d is Doppler frequency and f_0 is a carrier frequency.

In order to unveil if DIP can be considered as VS, derivation is needed to show if the same Doppler shift occurs in both cases, one where the source is at the VS location, and the other, where the source is at the DIP location. For that derivation, situation as in Fig 2 b) suggests that using DIP or VS as a source yields identical result, since relative speed between user and VS or DIP projected to line of connection between the user and either of these points is zero, and thus no Doppler shift occurs in either case. For derivation of situation as in Fig. 2 a) without reducing generality, but simplifying presentation and expressions, we shall observe a special case of Fig 2 a), where user is exactly at the shadow border, and DIP and VS are coplanar with user and diffraction-causing edge of the building, as depicted in Fig. 3.

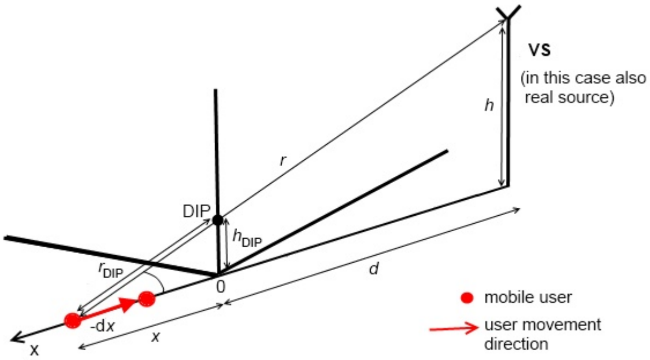

Figure 3 - Geometry of the setting, adjusted to derivation of doppler shift, either from DIP or VS. Fat lines represent edges of the building and base station mast and antenna

The easiest way of establishing expression for relative velocity user-source is by differentiation of their distance, here as a function of user movement. To calculate Doppler shift we shall assume that the user is moving radially towards the building corner, for a case of user being at the shadow border for simplified geometry, noting that it is applicable also for locations within the shadow, as explained in Fig. 2 a).

First let's do it for source being at VS, which corresponds to the real source in case of user being exactly at the shadow border. Doppler shift causing relative velocity v_0 is positive when distance between user and source is reduced, so:

$$v_{0\mathrm{VS}} = -\frac{\mathrm{d}r}{\mathrm{d}t} \tag{2}$$

where, from observing Fig. 2 a) distance r between user and VS can be expressed as:

$$r = \sqrt{(x+d)^2 + h^2} \tag{3}$$

where d is fixed distance between building edge and the base station and h is height of the base station antenna. From (3) it follows that:

$$\mathrm{d}r = \frac{x+d}{r}\mathrm{d}x \tag{4}$$

As user travels towards the corner, its location coordinate x is reduced, so user velocity is:

$$v_U = -\frac{\mathrm{d}x}{\mathrm{d}t} \tag{5}$$

and from (2) Doppler shift causing relative velocity is:

$$v_{0\mathrm{VS}} = -\frac{\mathrm{d}r}{\mathrm{d}t} = -\frac{x+d}{r}\frac{\mathrm{d}x}{\mathrm{d}t} = v_U\frac{x+d}{r} \tag{6}$$

If we assume that source is at DIP, incorrect relative velocity user-source is obtained. To calculate it, we start with time differentiation of distance between the user and DIP:

$$v_{0DIP} = -\frac{\mathrm{d}r_{DIP}}{\mathrm{d}t} \tag{7}$$

where r_{DIP} represents the distance between the user and DIP, as shown in Fig. 3. From similarity of triangles it follows:

$$r_{DIP} = \frac{x}{x+d}r = \left(1 - \frac{d}{x+d}\right)r \tag{8}$$

In this case, Doppler shift causing relative velocity would be:

$$v_{0DIP} = -\frac{\mathrm{d}r_{DIP}}{\mathrm{d}t} = -\frac{x}{x+d}\frac{\mathrm{d}r}{\mathrm{d}t} - \frac{d\cdot r}{(x+d)^2}\frac{\mathrm{d}x}{\mathrm{d}t} \tag{9}$$

and then using (6) to get rid of dr yields:

$$v_{0DIP} = \frac{x}{x+d}\cdot v_U\cdot\frac{x+d}{r} + \frac{d\cdot r}{(x+d)^2}\cdot v_U = \frac{v_U}{r}\left[x + \frac{r^2 d}{(x+d)^2}\right] \tag{10}$$

Finally, we can express v_{0DIP} using v_{0VS} expression in (6) to extract exact difference in obtained relative velocities:

$$\begin{aligned} v_{0DIP} &= \frac{v_U}{r}(x+d) + \frac{v_U}{r}d\left[\frac{r^2}{(x+d)^2} - 1\right] = \\ &= v_{0\mathrm{VS}} + v_U\frac{d}{r}\left[\frac{r^2}{(x+d)^2} - 1\right] = v_{0\mathrm{VS}} + v_U\frac{d\cdot h^2}{r(x+d)^2} \end{aligned} \tag{11}$$

In other words, the movement of DIP is not influencing Doppler shift, just as in propagation by reflection.The interaction point is moving as the user moves, but Doppler shift is depending only upon angles between the user trajectory and the angle of arrival. So, as seen in (11), the assumption of DIP movement contributing additionally to the Doppler shift would give an error of:

$$v_{err} = v_U\frac{d\cdot h^2}{r(x+d)^2} \tag{12}$$

where v_U=-dx/dt is the user velocity.

Thus, only VS as depicted in figures 2 and 3 is correct source position for calculating Doppler shift, whereas DIP is not, although it has intuitively attractive properties. These results oblige construction of geometry based channel models in such a way that they respect properties of correct virtual sources, in the first place their circular movement correlated with the movement of a user.

To wrap-up, diffraction mode of propagation “around the corner” has following properties:

a) when the user moves directly towards the corner, e.g. the DIP:
   - DIP is sliding along the edge

- there is a Doppler shift, but it needs to be calculated from relative velocity user-VS, and not from relative velocity user-DIP
- VS is stationary

b) when user circles around the corner, i.e. around the DIP:

- DIP is not changing, i.e. sliding along the edge
- there is no Doppler shift
- VS is circling as well

IV. CONCLUSION

The paper investigates how to model and calculate Doppler shift for diffracted rays, in ray-tracing pre-simulated environments, having in mind specific properties of diffraction, i.e. energy spreading along the Keller's cone.

Two possibilities were considered: (1) the model based on the location of DIP, which is convenient especially for multiple interaction rays, as this is also the last interaction that occurred before the user; (2) the model based on the location of VS, which corresponds to the reality. The only accurate result is obtained when VS is considered a source, whereas incorrect Doppler shift causing relative velocity is obtained when assuming DIP as a source. The results could also be expanded for multiple diffracted and/or reflected rays - derivation is straightforward, but more complex.

These results oblige construction of geometry based channel models in such a way that they respect properties of correct virtual sources, in the first place the correlation of their movement with the movement of a user. The fact that, due to diffraction, movement of virtual sources is highly correlated with user movement is interesting for further investigation. Using this fact one could investigate the possibility of the existence of uncorrelated multipath environments for uncorrelated users movements, and its potential for mitigating co-channel interference between users.

For reference channel model there is a need for further investigation to find feasible solutions with good trade-offs in terms of complexity and sensible closeness to reality. This is especially challenging for DRCMs where for implementation of mobility one needs to handle very detailed and complex data sets.

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