A spatially consistent radio channel model enabling dual mobility

Vuokko Nurmela
Nokia Research Center
Espoo, Finland
vuokko.nurmela@nokia.com

Pekka Kyösti
Anite Telecoms Oy
Oulu, Finland
firstname.lastname@anite.com

***Abstract*— In a future radio communication network various types of links will co-exist in the same area, and they need to be modelled consistently. We describe a channel modelling framework, which can consistently describe large and small scale phenomena of different types of links. The approach supports generation of spatially consistent radio channel realization also for cases where both link ends are moving like in device-to-device communication. Traditional cellular links and distributed antenna systems can be described with the same model, which allows a fair comparison between different types of transmission schemes. The main principle of the proposed framework is to create the propagation environment independently from the radios like in COST 2100 model. This is like simplified ray tracing without a map, i.e. without need of any detailed geometric or electromagnetic description of the environment as a prerequisite. The modelling principle and some examples of resulting radio channel statistics are simulated and presented.**

Keywords—radio channel, modeling, multi-link, device-to-device, shadowing

I. INTRODUCTION

In a future communication system various types of links will co-exist in the same area. Traditional cellular connections are going to be completed with smaller cells, pico- and femtocells, movable nomadic base stations and direct device-to-device (D2D) connections between user terminals. Also the density of the links is expected to grow tremendously. This sets requirements for channel modelling, as discussed in [1] and [2].

Consistent modeling of closely located links is a challenge, which has been discussed earlier in the context of peer-to-peer networks ([3], [4]). In a traditional channel model for cellular systems, where one end of the link is always fixed, auto- and cross-correlation properties of large scale parameters, e.g. shadowing can be modeled by pre-calculating a look-up table to indicate the parameter value in each point of the simulated area. When both ends of the link can be at arbitrary locations or can be moving, the size of a look-up table would make this approach unfeasible for a typical system simulation. Ignoring the large scale correlation can anyhow lead to incorrect conclusions, as demonstrated in [3].

Similar limitations are seen with earlier models, when the antenna array size is very large, i.e. when large scale parameters cannot be assumed constant over the whole array (see e.g. [5]). Also in such case each parameter needs to be a function of both RX and TX location.

Because of the heterogeneous structure of future networks, different kinds of links should be modelled in a consistent way. E.g. separate model for cellular and D2D may not be justified, but the properties of the channel should depend on the environment and e.g. height (from the ground level) of the radios.

Also consistent modeling of small scale parameters is going to be more important in the future. In widely used models of WINNER [6] or ITU-R [7] the scatterer directions are randomly drawn independently for each link. This means in practice that even close-by transceivers may see different directions of arrival (DoA) and directions of departure (DoD). Independency between links is unrealistic, since closely located terminals are likely to see the same reflections etc., and have similar angular characteristics. This is demonstrated in Fig. 1. Common propagation paths limit the gain of multi-user MIMO (MU-MIMO) or interference rejection techniques, because in many cases two terminals cannot be separated in angular domain. The impact of this is analyzed in [8]. As in the coming years multiantenna techniques become more important, and also network deployment becomes denser, it is more important that the similarity of closely located links is modelled coherently.

COST 2100 [9] model has solved this issue with scatterers being present in the environment, and not being specific to each link. It contains the concept of clusters and their visibility regions (VR). If a terminal is within a visibility region of a cluster, that cluster composes a path, and the DoA and DoD are towards that cluster. Two UEs close to each other are likely to see partly the same clusters, and thus have similar (not identical) angular characteristics. The problem with COST model is that it is designed for cellular links, and is not applicable in D2D, where both radios can be at arbitrary locations. Depending on the location of the TX, all clusters are

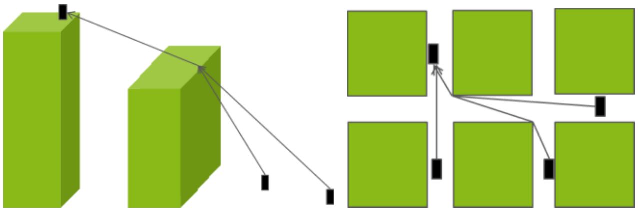

Fig. 1. Some examples of cases, where spatial separability of radios is limited by the propagation environment. Signals are coming from the same direction to the receiver, and thus multi antenna techniques cannot be utilized to differentiate wanted signal from interference.

not illuminated, and thus contributing to the received signal.

We propose to solve these issues by introducing a relatively simple, geometry-based stochastic model, where both large and small scale parameters of closely located links are modeled consistently. Spatial consistency also allows smooth and continuous time evolution of the channel parameters. This modeling approach has been created in the European 7th framework project METIS [10], to fulfill the requirements set by the project.

II. STRUCTURE OF THE MODEL

When the model is applied, the propagation environment is created randomly in the beginning of each simulation. The environment is the same for all mobiles, ensuring consistency of both large and small scale parameters.

A. Clusters

Clusters (i.e. scattering objects) are dropped into random geographic locations (x,y,z) with a pre-defined probability distribution. Optionally, the model can be utilized in (x,y) plane only. In a 3D model, the density of clusters should be height dependent, allowing realistic height dependency of propagation characteristics. The distribution of the clusters depends on the environment type, e.g. in isotropic rural or suburban environment the distribution is assumed uniform, whereas in urban environment with a street grid the distribution is modified to reflect the street structure, e.g. Manhattan. Clusters can also be placed more deterministically, if real 3D map of desired environment is available. Some clusters can be moving to describe moving objects.

B. Visibility regions

Each cluster has a visibility region (VR), like in COST-type models [9]. A cluster is visible to a radio that is inside the VR, but unlike in COST models, there is not necessarily signal coming through that cluster. The cluster needs to be illuminated by the TX in order to be seen by the RX. In COST models all clusters are illuminated by the base station, but if both TX and RX can be at arbitrary locations, this kind of assumption cannot be made.

If the TX and RX are within the VR of a same cluster, there is a link between them. (Line-of-sight and dual bounce links are explained later.)

The shape and size of the VR are parameters of the model and depend on the environment. In an isotropic case like rural or suburban macrocellular environment the orientation of the VRs is random, creating isotropic propagation characteristics. In urban environment the VRs should reflect the directions of the streets. For simplicity we have assumed that the cluster is at the center of its VR, but this is not required.

In a 3D model VRs also have a 3D structure. VRs are expected to grow as a function of height. This is physically intuitive, because from a higher location more objects are visible. The growth of VRs creates the desired height dependencies in the model. The growth rate at the function of height is yet another parameter. In urban environment a step-wise behavior is expected at the height of the rooftops.

Visibility regions have a characteristic called visibility gain. The concept of visibility gain is directly taken from the COST 2100 model [9]. It defines a smoothly increasing gain as the radio is approaching the VR center. The gain depends on VR size, wavelength, distance from the VR center and width of so called transit region. The transition region width may be specified, e.g. as 15% of the VR dimensions.

C. Coupling between clusters

To allow links longer than VR size, we define coupling between clusters. This is new compared to COST models. There is a dual bounce link between two radios, if the radios are located in VRs of two clusters, which are coupled with each other.

Two clusters may or may not be coupled. The probability of coupling decreases as the distance between clusters increases. Probability may also increase as the height of the clusters increases. The exact probability function depends on the environment. Coupling can also be deterministic, e.g. in an environment like Manhattan, where the visibility between objects can be derived from the street grid.

D. Line-of-sight coupling

To enable consistent modeling of line-of-sight (LOS), we want to avoid drawing LOS condition independently for closely located links. In the modeling approach areas of LOS are pre-defined when the environment is created. This is done by defining so called LOS-coupling between certain clusters. Two radios have a LOS path between them, if and only if they are located in VRs, which are LOS-coupled. The probability of LOS-coupling of clusters decreases rapidly when the distance increases, resulting into decreasing probability of LOS in longer links.

E. Radio link

After the propagation environment has been created as explained in previous section, all large scale parameters are deterministically calculated. To calculate the propagation, all paths of the link are added up. Each radio link can consist of three kinds of paths, as described below:

- Line-of-sight: A LOS path exists between two radios, if they are within VRs that are coupled with so called “LOS coupling”.
- First order interaction: A propagation path with a single interaction (reflection / scattering / diffraction) via a cluster exists between two radios if they are both within the VR of the cluster. The radios are in LOS to the cluster and signal propagates from TX to RX interacting with the cluster.
- Second order interaction: A propagation path with a second order interaction (reflection / scattering / diffraction) via two clusters exists between two radios if the first radio is within VR of the first cluster, the second radio is within VR of the second cluster, and the two clusters are coupled.

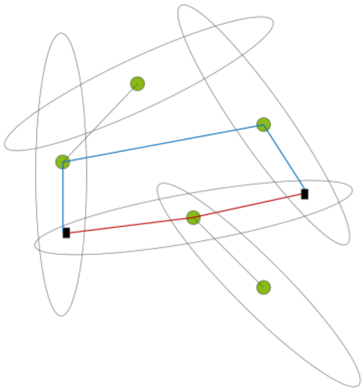

Fig. 2. Examples of clusters (green dots), visibility regions and coupling between clusters. The two radios (black boxes) are connected via one single interaction path (red line), because they see the same cluster, and one dual interaction path (blue line) because they see two clusters that are coupled. This is just an illustration, and for simplicity only a few VRs are presented. In the actual implementation the density of VRs should be bigger, not leaving a lot of gaps between them.

When the environment and the locations or trajectories of the radios are determined, the propagation is calculated purely based on the geometry and the antenna characteristics. The propagation delay is calculated directly from the path length. Angles of arrival and departure are based on the locations of the TX/RX and the locations of the first/last interacting clusters. LOS angles are calculated from the locations of TX and RX.

Various ways of calculating the path gains have been studied. In the current implementation the path gains are composed of free space path loss over each path segment, which corresponds to ideal scattering from a point-like object. To avoid creating a singularity near a cluster, the power is anyhow restricted to a constant level, when approaching a cluster.

On top of this, a random attenuation is added at every interaction. The attenuation is drawn independently for each cluster from the log-normal distribution with environment dependent mean and standard deviation.

In addition to the distance dependent attenuation and cluster specific attenuation the NLOS paths are also affected by the visibility gain. This means that the gain of each cluster is gradually going to zero towards the edge of the VR, to avoid sudden drop of power at the edge.

Neither path loss nor shadowing is modelled explicitly with any empirical path loss model or distribution of shadow fading. Instead they both result from the composition of path gains described above. Ricean K-factor is not modelled explicitly; it is determined as the ratio of power of the LOS path and the sum of other paths.

This approach provides a solution to the large scale parameter correlation problem in the case where both link ends can be at an arbitrary location, like in D2D. Realistic auto- and cross-correlation properties of e.g. shadowing are obtained implicitly.

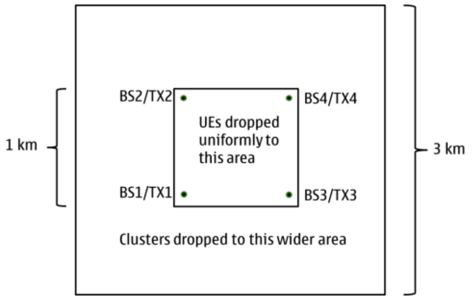

Fig. 3. Dimensions of the simulated world.

III. EXAMPLE IMPLEMENTATION

The cluster properties are the input parameters of the model. Since they are not straightforward to extract from measurements, applying the model requires testing with several combinations of input parameters, and looking for those who give the desired distributions of output parameters. We have created two example implementations to demonstrate this.

We have simulated propagation in isotropic environment modeling a typical macrocellular case, where h_{BS} = 25 m and h_{UE} = 1 m, and a D2D case, where $h_{UE1} = h_{UE2}$ = 1 m. The size of the example world is 3km*3km. The radios are located as presented in Fig. 3. To minimize border effects, the radios are dropped only in the middle of the simulated world.

In our implementation we have used elliptical VRs with cluster at the center of the ellipse. We chose elliptical shape, because it is mathematically simple, but unlike the circular VR in COST 2100 model, is not symmetric in all directions, i.e. the cluster can be seen further away in some directions. In the isotropic example, the orientation of ellipses is random.

The size of ellipses is exponentially distributed. The VRs grow as a function of height. This helps to create desired properties for cellular links. The base station, which is situated higher sees a lot of scatterers around the mobile station, whereas the mobile sees a more uniform angular distribution of scatterers. The growth of VRs also makes the path loss smaller for radios that are higher.

The probability of coupling between clusters depends on the inter cluster distance d

$$\Pr(d) = e^{-C\cdot d} \quad , \tag{1}$$

where C is so called coupling constant.

The probability of LOS coupling depends on the inter cluster distance

$$\Pr_{LOS}(d) = A_{LOS}e^{-C_{LOS}\cdot d} \, . \tag{2}$$

The power of each path segment is calculated as free space path loss (see Fig. 4)

$$P(d) = P_0\left(\frac{d_0}{d}\right)^2 , \tag{3}$$

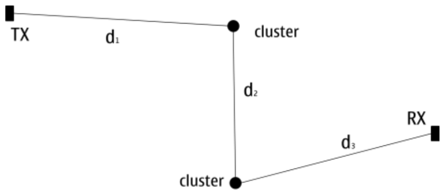

Fig. 4. Double interaction path TX-cluster-cluster-RX.

where P_0 is the power at the distance d_0. This constant part $P_0 d_0^2$ is modelled as log-normally distributed random attenuation, which is specific to each cluster. A physical interpretation of that is the size of the scattering object.

The power of a path is proportional to the product of all path segments, but limiting the power for very short distances:

$$power \propto \left[\frac{1}{\max(d_1, d_{\min}) \cdot \max(d_2, d_{\min}) \cdot \max(d_3, d_{\min})} \right]^2 . \quad (4)$$

The input parameters and their example values are presented in Table I. Those symbols mentioned in the text are also presented in Table I.

TABLE I. INPUT PARAMETERS AND THEIR EXAMPLE VALUES.

Parameter	***Symbol***	***Example value***	***Unit***
Cluster density		0.001	1/m^2
Mean VR major axis at ground level		100	m
Mean VR minor axis at ground level		10	m
Mean VR major axis at 25 m		2600	m
Mean VR minor axis at 25 m		260	m
Coupling exponent	C	0.003	1/m
LOS coupling exponent	C_{LOS}	1	1/m
LOS coupling constant	A	0.01	
Minimum effective distance	d_{min}	10	m
VR transit region width		15	%
Mean attenuation at each interaction		0	dB
Std attenuation at each interaction		10	dB

IV. RESULTS

Large scale parameters were extracted from a large dataset of 4 simulated TX locations and about 10,000 RX locations. The extracted parameters are presented in Table II.

The macrocellular parameters in Table II are rather similar than those given in [6], and a better match can be obtained by further adjustment of input parameters.

For D2D the comparison with existing parameters is not that easy, because there are not so many results available. Anyhow, the path loss is expected to be bigger when both radios are low, which has also been verified in measurements (e.g. [11]) Delay spread is smaller in D2D, because when the radio is lower, it sees less distant objects. Angular spreads are expected to be equal for both TX and RX in D2D, and the difference seen in these are due to random variations. In D2D the probability of LOS was small, resulting into few LOS cases, and thus statistics were not calculated for D2D LOS.

Path loss as a function of distance is presented in Fig. 5 and 6 for the macrocellular and D2D case, respectively.

TABLE II.LARGE SCALE PARAMETERS EXTRACETED FROM THE EXAMPLE SIMULATION.

	Macro-cellular LOS	***Macro-cellular NLOS***	***D2D NLOS***
PL exponent	2.0	3.4	4.9
Shadowing STD [dB]	0.2	9.9	12
Mean K factor [dB]	24	-	-
Mean delay spread [ns]	20	382	172
Mean ASD [deg]	2.6	29	34
Mean ASA [deg]	7.4	38	30
Mean ESD [deg]	0.46	3.6	4.0
Mean ESA [deg]	1.3	6.3	4.7

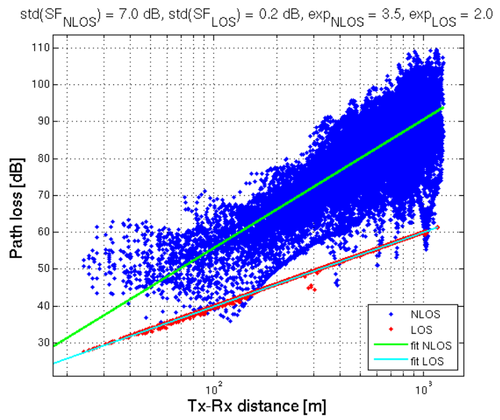

Fig. 5. Path loss as a function of distance, macrocellular case.

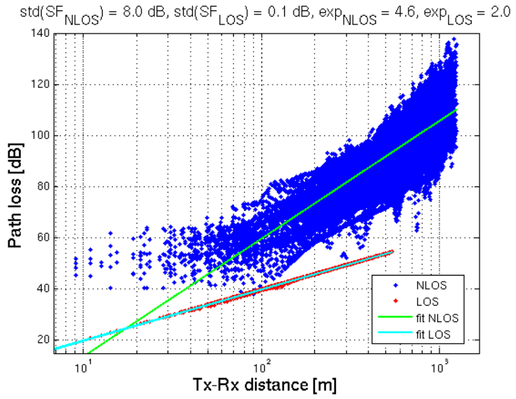

Fig. 6. Path loss as a function of distance, D2D.

TABLE III. SIMULATED CORRELATION COEFFICIENTS BETWEEN DIFFERENT MACROCELLULAR SITES.

	BS2	***BS3***	***BS4***
BS1	0.32	0.28	0.27
BS2		0.46	0.53
BS3			0.35

TABLE IV. SIMULATED CORRELATION COEFFICIENTS BETWEEN DIFFERENT TX LOCATIONS, D2D CASE.

	BS2	***BS3***	***BS4***
BS1	0.42	0.39	0.47
BS2		0.41	0.52
BS3			0.37

Also correlation of shadowing between the four simulated base stations was calculated, and the results are presented in Table III. These are in good correspondence with measurements e.g. in [12]. Similar correlation coefficients are also presented for D2D transmitters in Table IV.

Though one of the main advantages of this modeling approach is the possibility to obtain realistic correlation properties for the D2D case, this is unfortunately very difficult to visualize.

Some continuous routes were also simulated to demonstrate the time evolution of the channel. Path loss as a function of distance is presented in Fig. 7 for the macrocellular case. The received power is continuous as expected, because the impact of each cluster is gradually increasing and decreasing along the route.

Example power-delay profile on linear route locations is presented in Fig. 8. It shows smooth evolution of individual channel taps.

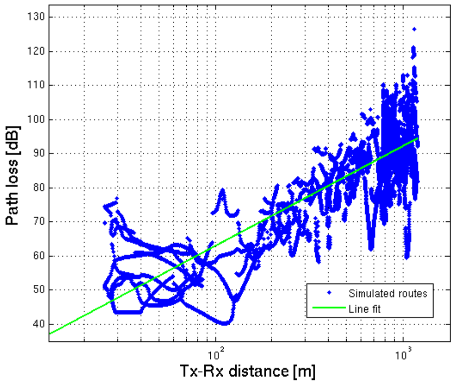

Fig. 7. Example of path loss on continuous routes.

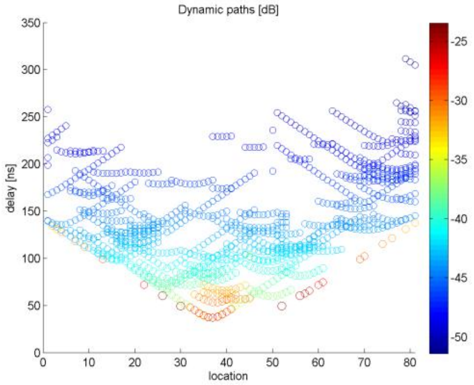

Fig. 8. Example time evolution of power-delay profiles.

V. CONCLUSIONS

We have presented a model that is computationally feasible, but still can model cases that are not within the reach of existing widely accepted models. The principle of the model is physically intuitive, like simplified ray tracing, but still with significantly lower computational burden. The model is based on COST 2100, but unlike its predecessor, it can describe links, where both TX and RX are at arbitrary locations. This is required when e.g. D2D links or very large antenna arrays are modeled. Correlation properties of large scale parameters like shadowing are obtained implicitly from the model, also in the dual mobility case. The model enables smooth time evolution, in a case where one or two users are moving. It can describe consistently directions of arrival and departure for closely located users.

An example simulation is presented, and propagation parameters are extracted and demonstrated for a macrocellular and D2D examples. They show similar characteristics as expected in real macrocellular and D2D measurements.

ACKNOWLEDGEMENT

This work has been performed in the framework of FP7 project ICT-317669 METIS. The authors would like to acknowledge the contributions of their colleagues, although the views expressed are those of the authors and do not necessarily represent the METIS consortium's view. The consortium is not liable for any use that may be made of any of the information contained therein.

REFERENCES

[1] J. Medbo et al., "Channel Modelling for the Fifth Generation Mobile Communications", in 8th European Conference on Antennas and Propagation (EuCAP 2014), April, 2014.

[2] T. Jämsä et al., "Deliverable D1.2 Initial channel models based on measurements". METIS project Deliverable, May 2014.

[3] P. Agrawal and N. Patwari, "Correlated link shadow fading in multihop wireless networks", IEEE Trans. Wireless Commun., vol. 8, no. 8, pp. 4024–4036, Aug. 2009.

[4] Z. Wang, E. Tameh, and A. Nix, "A Sum-of-Sinusoids based Simulation Model for the Joint Shadowing Process in Urban Peer-to-Peer Radio Channels". IEEE VTC-2005-Fall. 2005, pp. 1732 – 1736.

[5] S. Payami and F. Tufvesson, "Channel measurements and analysis for very large array systems at 2.6 GHz", in 2012 6th European Conference on Antennas and Propagation (EuCAP), pp. 433–437, Mar. 2012.

[6] P. Kyösti et al., "IST-4-027756 WINNER II Deliverable 1.1.2. v.1.2, WINNER II Channel Models," IST-WINNER2, Tech. Rep., 2007.

[7] "Guidelines for evaluation of radio interface technologies for IMTAdvanced, ITU-R Report M.2135," ITU-R, Tech. Rep., 2008.

[8] O. Gordon et al., "Inter-link multi-user MIMO channel capacity and the effects of clusters", IEEE 3rd International Conference on Communication Software and Networks (ICCSN), May 2011.

[9] R. Verdone, A. Zanella, "Pervasive mobile and ambient wireless communications, COST Action 2100", Springer, 2012.

[10] METIS, Mobile and wireless communications Enablers for the Twenty-twenty Information Society, EU 7th Framework Programme, http://www.metis2020.com.

[11] J. Turkka, M. Renfors., "Path loss measurements for a non-line-of-sight mobile-to-mobile environment", ITS telecommunications 2008.

[12] S. Jaeckel, et al., "Correlation properties of large and small-scale parameters from multicell channel measurements", 3rd European Conference on Antennas and Propagation, March 2009.