Propagation Modeling for Systems Beyond 3G

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Abstract—Introducing multi-hop (MH) and time division duplex (TDD) in high-speed wireless communication systems arise in challenges for system simulations, specifically in radio propagation modeling. In this paper a new propagation model is presented for systems B3G that make use of MH and TDD. The model is typically suited for urban and sub-urban scenarios with streets and many buildings where line-of-sight (LoS) and non-LoS (NLoS) conditions have to be distinguished. Different to conventional propagation models the new model reduces the required memory considerably. Instead of an exponential increase in the required storage space with the size of the scenario, the storage space increases only linearly when applying the new model, which is based on the idea to distinguish between LoS and NLoS conditions.

Keynotes — Multi-hop, system level simulations, TDD, NLoS, memory requirements.

1. Introduction
Mobiles radio systems beyond 3G will comprise one-hop and multi-hop (MH) communication [1]. MH communication is one interesting research area, especially in wireless self-organizing networks, often also referred to as ad hoc networks, where no long-term planned infrastructure exists. But even in infrastructure-based networks and fully meshed scenarios the introduction of MH communication with reduced transmit power and/or better link quality might increase the reliability of the link, respectively might exploit the scarce radio resource more efficiently [2]. Relaying can be most efficiently realized by means of time division duplex (TDD).

Introducing multi-hop and TDD in high-speed wireless communication systems arise in challenges for system simulations, specifically in radio propagation modeling. New communication constellations become possible, which have to be considered. Different to conventional FDD systems, in multi-hop TDD systems the received signal power and/or interference power between two mobile terminals has to be derived. For system simulations, where many transmitters and receivers, i.e. base stations (BSs)/access points (APs), relay nodes (RNs) and/or mobile terminals (MTs) are simultaneously active, the respective links have to be considered for realistic system performance estimations.

In this paper a new propagation model is presented for systems B3G that make use of MH and TDD. The model is typically suited for urban and sub-urban scenarios with streets and many buildings where line-of-sight (LoS) and non-LoS (NLoS) conditions have to be distinguished. Different to conventional propagation models the new model reduces the required memory considerably. Instead of an exponential increase in the required storage space with the size of the scenario, the storage space increases only linearly when applying the new model. With the new model, which primarily distinguishes between LoS and NLoS scenarios spanning an area in excess of 1 km x 1 km become tractable.

In Section 2 the challenges in radio propagation modeling for system simulations comprising MH and TDD are explained in detail. In the next Section 3 conventional approaches for radio channel modeling are discussed and the new approach is described. The comparison of the conventional and new approaches in Section 4 indicates a clear advantage of the new approach with respect to estimation errors and memory requirements. Besides a considerable lower memory requirement the new model inherits the benefit of being more precise in determination of the propagation conditions the smaller the distance becomes between transmitter and receiver.

2. Challenges in Radio Propagation Modeling for Systems Beyond 3G
Radio channel propagation modeling is a very complex task and several models for that purpose have been proposed [3]. Especially, for system simulations the propagation modeling has to be very simple and computational efficient due to many links that have to be simultaneously taken into account.

Systems beyond 3G will comprise TDD. It is known that TDD systems result in different communication constellations that do not exist for instance in frequency division duplex (FDD) systems. Unlike in FDD systems,
in TDD systems the uplink (UL) and downlink (DL) directions are not separated anymore in frequency and can interfere with each other. Typical communication constellations are depicted in Figure 1.

The first two examples a) and b) are conventional constellations in FDD and TDD systems. Neighboring mobile terminals (MTs) respectively access points (APs) generate interference at the victim receiver. In TDD systems the constellations c) and d) are possible, too, as far as the DL and UL is scheduled in neighboring cells at the same time. This is commonly known as the challenge arising from the variable switching point for DL and UL transmission. Specifically for 4G systems the direct-link (DiL) between MTs generate new signal-to-interference constellations, which are shown in the examples e) and f) in Figure 1. The DiL can be used for direct communication between neighbored MTs or for relaying data. Specifically, in the latter case one MT acts as relay node (RN). All three scenarios d) – f) make system simulations, in particular the radio propagation modeling, much more complex since the link of the wanted signal and/or the interference link exist between two MTs, and hence, arbitrary positions. As result, the radio propagation condition between any two possible positions in the simulation scenario has to be determined. This can be done either beforehand, which ends up in huge memory requirements, or during simulation, which results in high computational complexity that increases with the number of active links.

3. Propagation Models for Simulations

The attenuation of a transmitted narrow-band signal can be modeled as combination of three main parts:

1. Path loss, which monotonously increases with the distance between transmitter and receiver;
2. Shadowing, also sometimes referred to as long-term fading, owing due to obstructions by buildings;
3. Multi-path fading, also referred to as short-term fading, due to constructive and destructive interferences of reflected, diffracted, and scattered signals at the receiver.

Different to link-level simulations where complete channel states including multi-path propagation have to be modeled in detail, system simulation models primarily consider the main parts that are relevant for the received signal and interference power, i.e., the path loss and shadowing. In many cases the multi-path fading is simply taken into account implicitly in the mapping process from the calculated signal-to-noise-and-interference ratio (SINR) to the resulting packet error rate (PER). In the latter case, multi-path fading can be split in two processes, the multi-path fading on the useful link, and a joint process of all interference signals. Both processes can be modeled by a random process that follows a Rayleigh distribution with different values for the variance. However, the specific modeling of the multi-path fading is not subject of this paper and, hence, will not be considered any further in the following.

There are a lot of models to forecast the path loss but most of them require complex calculations and a lot of additional information, e.g., the sizes and location of buildings, which make them unsuitable for system simulations. One important characteristic, which many models make use of, is that the path loss and shadowing can be modeled as time-independent components. Hence, it is proposed in many models to determine these values beforehand via pre-calculations. The values for the path loss and shadowing can be jointly stored in a so-called attenuation loss maps. This reduces the required calculation time during system simulations considerably and still achieves very good and precise propagation predictions.

In the following sub-sections two different approaches are presented how these values can be efficiently stored and assessed during system simulations. The first approach, referred to as the square approach, is the commonly used model for typical system simulations. The second, new approach is called LoS/NLoS approach in the sequel and makes use of the physical behavior of electromagnetic waves in the considered deployment scenarios under investigation.

3.1 Square Approach

It is assumed that a precise attenuation loss map exists, which has been provided for example by means of real measurements. The most obvious and commonly used model stores these pre-determined attenuation (path loss and shadowing) values for all possible pairs of transmitter and receiver in rectangular squares, which cover the whole scenario under considerations where MTs can move. It is assumed that the square segments have a side equal $a$ meters. If more values for one square segment exist from predetermination, the mean value will be calculated.

The square approach has the advantage to be very flexible, since predetermined values of any radio propagation model or even real measurements can be used. A second advantage is the high computational speed. Because attenuation values are calculated beforehand and are stored in an array a minimum of time is required to retrieve the attenuation for any transmitter-receiver pair.

1. Memory requirements

However, the most dominant disadvantage is the high memory requirement to store all attenuation values. Thus, this approach is unsuitable for simulations of large scenarios using MH and TDD, i.e. for simulations where attenuation values for all possible transmitter and receiver constellations have to be available, as will be shown in the next Section 4.

2. No relationship between attenuation and distance
Another disadvantage of the simple square approach is that it does not take into account the fact that attenuation values changes more rapidly when the distances between the receiver and transmitter are small. A possible solution to this problem would be to introduce smaller segment sizes near to the transmitter and larger ones as the distance increases, which ends up in variable segment sizes. But this might result in even higher memory usage than the constant segment size approach. With different segment sizes an optimized storage of values, which makes use of the bidirectional behavior of the attenuation and, hence, symmetry in the values stored in the array, cannot be exploited anymore, and the memory cannot be reduced by a half like this is possible for constant segment sizes.

3. Quantization error
Due to the selection of squares that are represented by one attenuation value only, there are quantization errors when traveling from one segment to another. One approach would be to introduce some kind of interpolation between neighboring segments or a calculation of an interpolated values based on the gravity of all adjacent segments. However, this would increase the complexity in calculating an attenuation value instead of simply accessing one value from an array.

4. No utilization of correlation
Square segmentation does not support the reduction of the memory usage, using the fact that neighboring attenuation values are often correlated. Indeed, the most significant changes in pass loss values are concerned with LOS/NLOS condition between the transmitter and receiver. On the other hand close segments in LOS areas (as well as in NLOS) are usually strongly correlated.

3.2 LoS/NLoS Approach
The LoS/NLoS approach separates the whole area in sectors and distinguishes between an LoS and NLoS region for which corresponding attenuation exponents for a simple path-loss model are calculated, see Figure 2.

The approach uses the square approach as a basis. From the perspective of a receiver, the center of an arbitrary square segment is used to launch rays dividing the map into areas, which are called sectors for simplicity. The angle between consequent rays, \( \alpha \), is constant for all rays and all segments on the map. The number of sectors \( n \) is a system parameter. E.g., \( n = 18 \) sectors are defined in Figure 2. For each sector it is stored the LOS/NLOS radius. For sector 1 and sector 15 the respective radius is shown in Figure 2. Two situations can be distinguished: LOS – for distances smaller than this radius and NLOS – for larger distances. It is assumed that in urban areas there is the following typical situation: If in the given direction for some distance NLOS condition holds, there is a high probability that this condition will be true for even larger distances in the same direction. For transmit antennas below the roof-top or only slightly above the roof-top this condition holds in most of the cases.

The next step is to calculate attenuation values for distances smaller and larger than LOS/NLOS-radius. One approach, which is proposed in this paper, takes into account the predetermined values stored in the square segments with high granularity. It is assumed that the attenuation value (if measured in dB) for each sector equals to \( L_0 + \gamma \log(d) \), where \( \gamma \) is a attenuation exponent, which takes two different values \( \gamma_1 \) and \( \gamma_2 \) for LOS and NLOS situations, respectively. \( L_0 \) is a constant attenuation shift (which also can be different for LOS and NLOS cases), which is assumed to be equal for all sectors and, hence, is a system parameter. Three approaches exist for calculating the attenuation exponent values: First, the values can be calculated for each sector individually. All square segments with LOS (NLOS) located in the respective sector are taken into account to derive the mean value for the LOS (NLOS) attenuation value by means of curve-fitting. This approach is called “LoS/NLoS with sector specific exponent” in the sequel. Second, two values can be stored per square segment, representing the mean attenuation exponents for LOS and NLOS for all sectors. This approach is called “LoS/NLoS with segment specific exponent”. And as third option, there exist only two common system wide values \( (\gamma_1, \gamma_2) \) for all sectors and segments. This approach is referred to as “LoS/NLoS with system-constant exponents”.

Both values, for the second and third approach, could be calculated as the mean of the respective values of the previous approaches.

The advantages of the LoS/NLoS approach are that it inherits the advantages of the square approach, since it is based on it, but avoids most of the disadvantages of the square approach. E.g., it considerably reduces the required amount of memory, takes into account the need for higher precision with decreasing distance between transmitter and receiver, and makes use of the correlation between attenuation values since it distinguishes between LOS and NLOS.

Figure 2. LoS/NLoS approach with \( n = 18 \) sectors
Nevertheless, the new approach has also some disadvantages, which one of it is the simplicity of the attenuation formula that is parameterized but cannot take into account all propagation effects. But these differences are quite small as will be shown in the next Section 4, and become even smaller the closer the transmitter and receiver are located. Moreover, if other, more complex attenuation formulas are parameterized and the LoS/NLoS approach with sector specific exponent is used the interpolation error can be reduced even more but on the costs of a slight increase in the required memory. Another obvious disadvantage is restriction with respect to the scenarios. It is assumed that after the LOS/NLOS radius there are only NLOS conditions. This is true in most of the cases for antennas located close or below the roof-top. However, if this condition is not true anymore, the model has to be extended. One possible solution is to introduce more than one LOS/NLOS radius to encode the information about LOS and NLOS. This increases the complexity and memory requirements of the model only slightly. Nevertheless, the additional amount of required memory still needs to be determined.

In summary, the new approach has many advantages and the disadvantages can be circumvented at the expenses of slight increases in complexity and memory usage.


In the following the accuracy and memory requirements of the square and LoS/NLoS approach are determined. For the accuracy the difference in the attenuation is used as metric.

4.1 Difference in Attenuation

In the following Figure 3 the difference between the pre-calculated values and the attenuation values derived by the LoS/NLoS approach for a 300 m x 300 m scenario are shown. The predetermined values serve as reference and have been resolved with a very fine granularity of square segments ($a = 1$ m). To obtain realistic reference attenuation values, the Walfish-Ikegami (WI) model has been used in a Manhatten scenario. The attenuation values with the LoS/NLoS model have been derived with system-wide attenuation exponents. From the results it can be concluded that the LoS/NLoS approach precisely predicts the attenuation values with negligible differences of less than 3 dB. Of course, if the exact equations for LOS and NLOS of the WI model would have been used in the LoS/NLoS model instead of the simplified distance-dependent attenuation model, there would not be any difference at all.

Different to that, the square model using a reasonable segment size of $a = 10$ m indicates a clear influence of the segment size on the quantization error. The relation between the transmitter-receiver distance and absolute difference in the attenuation values for the square approach is shown on Figure 4.

![Figure 3. Signal and interference scenarios](image1)

![Figure 4. Relation between the transmitter-receiver distance and absolute quantization error](image2)

For distances below 50 m the errors are typically between 2 – 7 dB. However, with increasing distance the absolute errors decrease. But this is in contrast to the requirement of a good model to have very precise estimations for small distances.

4.2 Memory Requirements

To estimate the required memory of the different approaches a simple example is introduced first. For a Manhattan scenario ($x = y = 550$ m) and segment size, $\alpha = 10$ m there exist $l = 3025$ segments. The square approach requires in this case $(l^2 + l)/2 = 4576825$ attenuation values. If float variables are used, which require 32 bits of memory for each value, approximately 18.3 MB of memory is needed for the square approach. In the case of larger scenarios ($x = y = 1000$ m) and smaller segment size $\alpha = 1$ m, we will need
approximately 2000 GB of memory, which is not manageable for currently existing computers. Different to that, for the LoS/NLoS approach with sector-specific exponents exactly \( 3 n \) float values have to be stored. This can be even reduced for the LoS/NLoS approach with system-constant exponents to \( n \) float values only.

In the following Figure 5 the memory usage for different number of segments are shown for the different approaches.

![Figure 5 Memory usage for “square” and “LoS/NLoS” approach](image)

Future investigations will concentrate on the adoption of the model to wide-area scenarios with very high transmit antennas, where LOS and NLOS will alternate even in the same direction and, hence, where no clear distinction between LOS and NLOS can be simply made in one direction by means of one radius only.

In addition, the model will be adopted towards the introduction of multiple-input multiple-output antenna systems. Except the adding of further values characterizing the channel transfer function in each sector, in particular the eigenvalues or an indicator value describing the spatial correlation between the channels, it is expected that the same idea can be used as a basis. In addition, the characteristic of the energy distribution over the space, specifically with the introduction of beam-forming, should be taken into account at the positions of active transmitters.

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### Reference

