One Further Step Towards Realistic Simulations of Wireless Networks

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The realistic simulation of the lower layers in the protocol stack, namely the physical layer of a wireless ad-hoc network is known to have a severe impact on the outcome of simulation results. This work focuses on the effects of simulating realistic radio propagation and on the possibility of simulating realistic radio propagation with event based network simulators. Based on an available implementation of Ricean/Raleigh fading, we did evaluate the possibility of realistic simulations with the ns-2. The main focus was on the ability of simulating grey zones accurately. The propagation characteristics of the model was then calibrated to measurement results that were obtained from multiple experiments with notebooks, equipped with wireless LAN adapters. We did also compare the outcome of simulations using generic, simplistic propagation models that are commonly used for evaluating wireless protocols with our more realistic model, showing that the usage of a realistic propagation model has a severe impact on the performance of a wireless ah-hoc routing protocol.

1. Introduction

1.1. Motivation

Wireless networks become more important every day. As the importance of these networks grows, also new application areas of these networks are uncovered. Apart from the currently used infrastructure based wireless local area networks, mobile ad-hoc- or even sensor networks with a large number of nodes are currently planned and operated. These networks have new requirements with respect to routing and to the provided quality of service features. The energy efficiency of the communication system is also becoming more important as the networks become more and more autonomic, so new protocols need to be developed that account for these new requirements.

Simulations are an important tool for protocol developers, because protocols cannot be tested completely on the variety of possible network topologies with reasonable effort. Actually, much of the protocol validation and performance assessment is done by using simulations of networks. The outcome of these simulations strongly depends on the accuracy of the used simulators and the used simulation models. Currently, many simulation studies are conducted without considering the realism of the simulators used. The effects of the simulators inaccuracies on the outcome of the simulation is usually also not considered.

When simulating a wireless network, the simulation of the whole network can be divided into the simulation of the multiple network layers. Depending on the type of the simulation – whether the simulation is conducted for validation or for performance assessment reasons – the required accuracy on the different layers may be decreased. However, the consequences of decreasing simulation accuracy must be known. Often, the accuracy of a specific simulation is not taken into account, resulting in simulation results that are questionable or even unusable. As it will be pointed out in this work, the accurate simulation of the lower layers in a protocol stack, namely the physical layers, has a severe impact on the outcome of a simulation.

This report covering our current work in progress regards the accuracy of the simulation of the physical layer of wireless networks and the effects of increasing and decreasing its simulation accuracy. Furthermore, our realistic propagation models are introduced, their creation is described and their creditability and accuracy is evaluated.

1.2. Related work

The accuracy deficits of current simulations of wireless networks are already a subject of discussion in current literature. [HBE01] provides experiences about the effects of detail in wireless simulations with respect to the accuracy of the used radio propagation model. Unfortunately, only the case of open terrain is considered in this work. [TMB01] evaluates different physical layer models that ship with popular network simulators, namely ns-2 [NS2] and GloMoSim [GMS], and points out the effects of changing relevant parameters at the physical layer to the simulated protocols at network layer. Unfortunately, no measurements with real hardware that could be used to determine the correct settings for the physical models are documented. However, the paper documents the significant changes to the achieved protocol performance, when the used radio propagation model is changed. The work described in [LYN04] second the claim regarding the effects of radio propagation models from [TMB01]. However, also in this work, unfortunately no methodology for achieving meaningful simulation results is presented. [CSS02] compares the outcome of simulations that have been conducted by three major network simulators. The differences in the simulation outcome show again the need for realistic simulation models – otherwise the simulation results might be meaningless. At least partially the differences between the simulators that have been experienced in [CSS02] seem to come from different implementations of the physical layer – this proves the need of a methodology for creating and validating a model for the physical layer of a simulation. The work of [KNG04] falsifies five axioms that are used in many currently used physical propagation models. In [GKN04], the impact of physical propagation on routing and application level performance is shown again.

The work presented in [DG05] shows some interesting effects of real wireless networks that are currently not completely covered by simulators yet. However, these effects may influence the performance of the simulated protocols significantly. Especially the relationship between the size of a packet and the probability of receiving it correctly is not modelled yet in network simulators. Also the effect of grey zones and interference ranges is not yet considered in most performance assessments of routing protocols, due to over simplistic propagation models that are being used for performance assessment [LNT02]. Although most simulators are capable of modelling these effects – depending on the radio propagation model that is being used, there are very few works that actually make use of these radio propagation models. A promising propagation model is the Ricean and Raleigh fading model [PNS00], that can be combined with the shadowing model that ships with *ns*-2.

All of the works mentioned above document the need of an accurate, predictable, physical propagation model. At least a methodology for performing realistic simulations on the physical level of a wireless protocol stack is required. Although the differences in the achieved simulation results, depending on the radio propagation model used, show the need of a realistic radio propagation model, there is no work that answers the question on how to obtain such a model. The works presented in [LYN04] and [GKN04] even proof, that an inaccurate or wrong radio propagation model could void the simulation results. Since most of the performance assessments of routing protocols are made with simplistic propagation models, their results could be considered being questionable due to the inaccuracies of current physical propagation models that are laid out in the works mentioned above.

Two methodologies are currently used to overcome the problems associated with inaccurate physical models: Network emulation and providing additional information to the simulation from experiments. Network emulation uses *testbeds* of real hardware, either connected wired or wireless to each other to emulate a realistic network. Two types of testbeds can be separated: Wired testbeds and wireless testbeds. Wired testbeds consider of a number of wireless network cards that are connected by wires to a black box rather than to a real antenna. This box simulates the physical propagation of the network, depending on the simulation positions of the network nodes. Although these testbeds use the same Mac-Layer implementation as a real network card, as well as the same code for the upper layers of the protocol stack might be used, they also suffer from the problem of providing an accurate radio propagation model. Wireless testbeds use nodes that are equipped with wireless network cards and real antennas. Although these network emulators do not have the need of simulating the radio propagation – they have the problem of being unable to provide radio propagation models for different environments. Also the correct and accurate simulation of movements is problematic due to generated interference by the wireless nodes.

A further problem that may affect the outcome of simulation studies is the implementation of the code itself. Usually, simulators come with the own implementation for used Mac-Layers and network protocols, requiring the developer to implement the protocols to be simulated again for every simulator that is to be used [LYN04]. Simulators that are capable of directly executing production code, like SWAN [LYN04] or ns+SDL [KGGR05] can overcome this problem of having duplicate code in separate code bases.

1.3. Goals

The first goal of this work is to assess the current situation of protocol validation and performance simulation. A set of simulations with the goal of comparing the impacts of physical propagation models to a set of ad-hoc routing algorithms is to be performed. Afterwards the possibility of performing realistic simulations should be evaluated. Therefore, multiple experiments are to be conducted for creating multiple realistic radio propagation models. We want to evaluate whether these models can be used to achieve realistic and meaningful simulation results.

Although the layers above the physical layer are not the main concern of this work, the effects of these layers should also be concerned. Especially an inaccurate modelling of the MAC layer could result in unwanted simulation results.

1.4. Outline

The remaining part of this work is structured as following: Section 2 will survey deficits in current simulation studies; Section 3 will discuss the simulation accuracy that is achievable with event driven simulators. Section 4 presents the configuration and the results of our experiments for measuring wireless propagation. In Section 5, we shortly introduce the propagation model that we have created from the data collected during our experiments. Section 6 presents the results of our simulation studies with conventional and with our newly created radio propagation models. Section 7 gives a short conclusion and Section 8 presents further work in this area.

2. Deficits in current simulations

In current literature, several causes for inaccurate simulation results are outlined. The most evident reason for inaccurate simulation results is the implementation or parameterization of the simulated components themselves. In this work, we separate three layers of simulation: The simulation of the physics, which is represented by the components that simulate the physical layer and the radio propagation of a network, the simulation of the hardware, represented by the component that simulates the MAC layer and the simulation of the software system that is to be evaluated. The software system includes the simulated application and all simulated protocols, including transport protocols and those protocols that are being evaluated by this simulation. The next paragraph will describe the possible inaccuracies caused by these components in greater detail; the following paragraphs evaluate possible workarounds that are currently being used in literature.

2.1. Sources of inaccuracies in current simulation studies

Currently, there are many works that evaluate protocols by using simulations. Most of these works consider routing protocols and most of these simulations are conducted by using a simplistic propagation model, like free-space or the two-ray ground model that ships with *ns*-2 for simulating the radio propagation within the wireless network. The work presented in [TMB01] proof that different physical propagation models affect the outcome of simulations significantly. The accuracy discrepancies of current radio propagation models do not only affect simulations of low-level protocols, [TMB01] shows, that also protocols on higher layers are affected. We will show in this work that simplistic propagation models can even completely void simulation results, but also that it is possible to conduct realistic simulations by using event driven simulators.

In the works mentioned above, the well known propagation models that are supported by the most common network simulators are compared. These models can be divided into two types of propagation models – deterministic propagation models and statistic propagation models.

When using deterministic propagation models, the received signal strength solely depends on the range between the transmitter and receiver node. These models differ in the assumptions that are modelled by the possible parameterization. For instance, the free space model [Fri46] assumes perfect propagation conditions with a direct line of sight, while the also popular two-ray ground model [Rap96] also considers the reflection of the signal on the ground. In contrast, statistic propagation models like the shadowing model [Rap96] consider also random effects when calculating the receivers signal strength. As a result of this, the area where a signal can be received is not anymore an ideal circle. The borders of this area make up the so called grey zone – this is a zone where the transmitters signal can be seen, but can only be correctly received with a certain probability. This probability decreases with increasing distance to the sender, modelling the reality more accurate than the deterministic models. However, statistical models require accurate parameterisation.

The work presented in [LNT00] presents more factors that must be considered when simulating a radio propagation model. Current models do not account for different transmission speeds and for the size of a transmitted packet. Since most packets are dropped due to numerous bit-errors, smaller packets have a higher probability of being successfully received than larger packets. Sometimes, even more simplistic propagation models, like AWGN channel models, that are simply capable of dropping packets due to a random distribution are used. It seems to be evident, that most simulation studies rely on simplistic propagation models, yielding most of their results questionable.

The simulated MAC-Layer does also contribute to the creditability of the overall simulation results. [TMB01] indicates possible discrepancies due to wrong parameterization of the 802.11 MAC layer. After applying correct parameters to the MAC layers, all simulators gave almost equal results. Although most of this work will focus on the effects of the simulation of the physical layer, however, when an accurate simulation of the radio propagation is possible, the accuracy of the MAC layer must also be assessed to ensure creditable simulation results.

Also the simulated software must be considered when assessing the achievable creditability of a simulation. [LYN04] mentions the technique of directly executing production code in the simulator. This ensures a common code base for simulation- and production systems. It also guarantees the absence of errors due to implementing an already tested code again for a specific simulator. Unfortunately, with current simulators, it is necessary to re-implement a protocol for every simulator that is to be used, making comparisons between different simulators a time consuming task. With *ns*+SDL [KGGR05], we have presented an extension to the *ns-2*, that is capable of directly executing protocols, that have been specified in SDL – without having to adapt the protocols to the simulator.

The applications are usually modelled by using CBR or VBR traffic generators. To evaluate whether these generators affect the outcome of simulations is beyond the scope of this work. The same holds for the used movement model, if any movements are part of the simulated scenario.

2.2. Testbeds and network emulation

Testbeds and network emulation are proposed as an alternative to simulation studies. These techniques use real hardware instead of a completely simulated network to emulate a wireless network with a specific topology. Due to the considerable effort, that is required for creating such a testbed, only very few testbeds are currently available. All testbeds are limited with respect to the number of nodes, and, depending on the type of the testbed, with respect to the topology that can be simulated. Testbeds that use real wireless LAN hardware are problematic when different environments or movements are to be simulated, due to the fact that always the propagation characteristics of the testbed are used. Testbeds that simulate the radio propagation suffer from the same problems that simulators suffer from – the creditability of the simulated propagation model must be ensured.

2.3. Connectivity traces

Another possibility of overcoming some problems of inaccurate radio propagation models are connectivity traces. These traces are created during experiments and store whether a node is currently visible or not. This information is used by the radio propagation model then to help with the decision whether a specific packet can be received or not. These traces have the advantage that they can be more accurate than current propagation models. For example, the probability of being dropped due to bit errors is higher for larger packets. As a result, smaller packets have a higher success ratio of being received at a higher distance from the sender node than larger packets. Unfortunately, connectivity traces are only available when an experiment with identical topology has been conducted. This is not feasible for most simulation studies due to the considerable effort that has to be spent for conducting experiments, especially when multiple protocols are to be assessed using multiple, and very large topologies. Also, there are protocols that simply cannot be assessed by experiments or emulation due to the lack of suitable hardware, so simulations will remain important, regardless of the creditability concerns associated with some of them.

3. Achievable accuracy

Our first goal was to assess the currently achievable simulation accuracy. Therefore, we did perform simulations of several multi-hop routing protocols. Since our main concern is the physical propagation model, our first concern was to eliminate inaccuracies that could be caused by the simulation of higher protocol layers.

3.1. Minimizing negative effects of simulated layers

Three main sources of non-realism can be identified:

- The physical characteristics
- The simulated hardware
- The simulated software

This work will focus on the simulation of the physical characteristics, trying to minimize the inaccuracies produced by the simulated hardware and simulated software to a minimum. The following techniques are being used to achieve this:

The simulated hardware is only being used to a minimum required extend. Wireless LAN is being used only for broadcast transmissions at MAC level, not using simulator implementations for MAC-layer acknowledges, retransmissions and RTS/CTS mechanisms. The required time for sending a packet and the delay between packets has been measured with a real network card and special software, and has been compared with the results of the *ns-2* simulation of 802.11b. Also, all parameters of the MAC-layer have been set very carefully.

For the simulation of our routing protocols, we did use ns+SDL [KGGR05], a simulator that allows us to directly execute protocols specified in SDL in a simulation. Since it is also possible to create an executable system for experiments by using the same compilers, this gives confidence about the accuracy of the simulated software. Furthermore, raw data are being sent through the simulated network, eliminating inaccuracies that could be introduced into the simulation by a incorrectly simulated UDP or TCP protocol.

3.2. Evaluation

The results from the simulations show that the use of different radio propagation models does not only affect protocol metrics, but also the collected application level metrics. A problem of many ad-hoc protocols seems to be the handling of grey zones. While they are present in reality, they are often omitted in simulation studies, because simple, deterministic propagation models are not capable of simulating them. One specific effect of grey zones, that is a considerable problem for ad-hoc routing protocols is the fact, that small packets tend to have a greater probability of reaching the receiver than larger packets. Since the control packets that are often used for assessing a route will have a higher probability of being correctly received, this will usually cause the routing protocol to select routes that are not capable of transmitting larger packets reliably [LNT00]. As it can be seen in the simulation study, this causes a huge performance degradation of the routing protocol.

3.3. Achieving simulation accuracy

For being able to conduct accurate simulation studies, all possible sources of inaccuracies should be removed as far as possible. For our simulations with *ns*+SDL, we were able to reduce the inaccuracies from the simulation of the hardware and from the simulated software to a minimum. So we will focus on the simulation of the physics, remarkably the radio propagation model in this work.

For being able to create an accurate radio propagation model, we did perform numerous experiments. The next Section will more closely describe these experiments and their results.

4. Experiments

A realistic radio propagation model needs to simulate the radio propagation in reality with the accuracy that is required for performing accurate simulations. We did perform a large number of measurements to collect data from multiple environments for building a set of realistic radio propagation models.

4.1. Description

All experiments were conducted by using two notebooks as transmitter and receiver stations. The transmitter node did use a modified version of the MadWifi [MAD] Wireless LAN driver that enabled us to lock the transmission speed of the ad-hoc transmissions to a specific value.

We did transmit raw broadcast packets to remove any RTS/CTS packets or MAC-level acknowledgements and retransmissions. The receiver node did use a packet capturing software that was capable of also receiving erroneous packets. For the connectivity measurements, only valid packets have been counted, as they would have been seen by the higher level protocols in the protocol stack.

We did conduct the experiments with two different transmission speeds, 2 MBit/s and 11MBit/s and in the following different terrain types.

- Woods without brushwood, flat terrain
- Woods without brushwood and with slope
- Woods with brushwood, flat terrain
- Woods with brushwood and slope
- Plain, flat terrain
- A parking lot with cars on it

The following data has been collected during each of the experiments

- The type of the terrain
- The slope of the terrain
- The orientation of the nodes antennas
- The transmission speed used
- The range between each of the nodes

4.2. Results

The experimental results did show, as expected, the presence of a grey zone. The grey zone is a zone around the transmitter node, where the possibility of receiving a transmitted packet decreases with increasing distance to the transmitter. The measurements did also indicate that the size of the grey zone varies with different terrain types. An interesting fact is that, even if the absolute size of a grey zone varies, its basic characteristics are always the same. Figure 1 shows the connectivity around a stationary transmitter node, measured by a receiver node that is slowly moving away from the transmitter. Three sections can be distinguished: the white zone where the signal reception is unlikely to fail due to propagation characteristics, the grey zone where the reception is uncertain and the black zone, where almost no packets are received correctly.

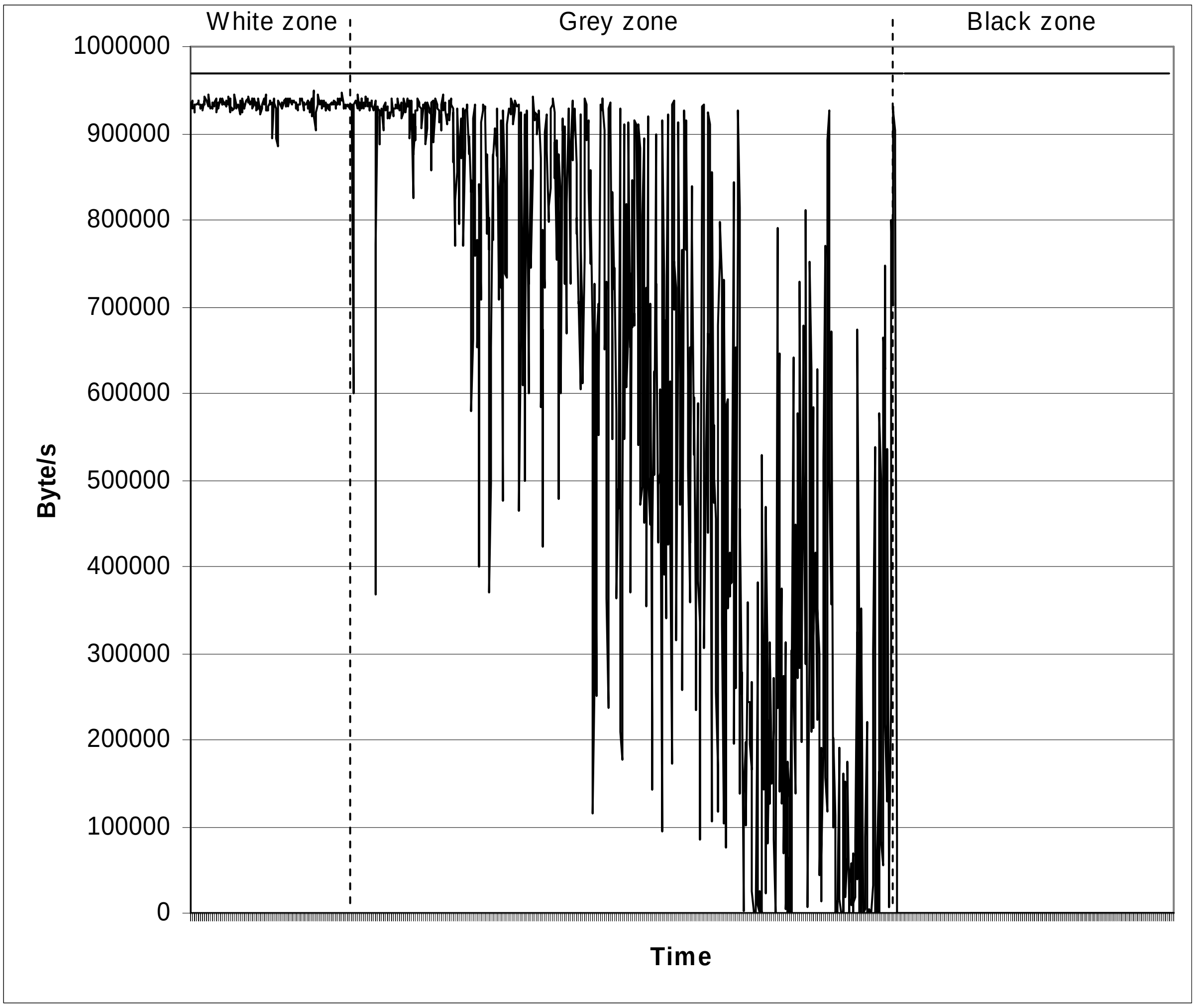


Figure 1: connectivity of a node moving slowly away from the transmitter

Figure 1 shows the measured connectivity of a receiver that slowly moves away from the sender node. Since the sender node transmits data at a constant rate, the measured received bits per second indicate the loss due to propagation characteristics. The measurement shows that in reality the connectivity does not decrease gracefully, but that oscillations are being introduced in the number of received bytes per second. The impact of these oscillations rises with increasing distance to the sender. However, there are still short periods of time where maximum connectivity is achieved. The following Figures 2-6 show measurements with stationary transmitter and receiver nodes. Especially the different propagation characteristics of the grey zone, shown in Figures 3-5 are interesting. The connectivity trace of Figure 3 has been measured with the receiver being at the beginning of the grey zone, the connectivity trace shown in Figure 5 was measured with the receiver being at the end of the grey zone. These stationary measurements confirm that the connectivity between two nodes that are slowly moving away from each other does not decrease gracefully. They also do indicate that there are still periods with certain connectivity when the receiver node is within the black zone. This is important and should be kept in mind when protocols that measure the connectivity between nodes are designed, or if they are evaluated by using simulations.

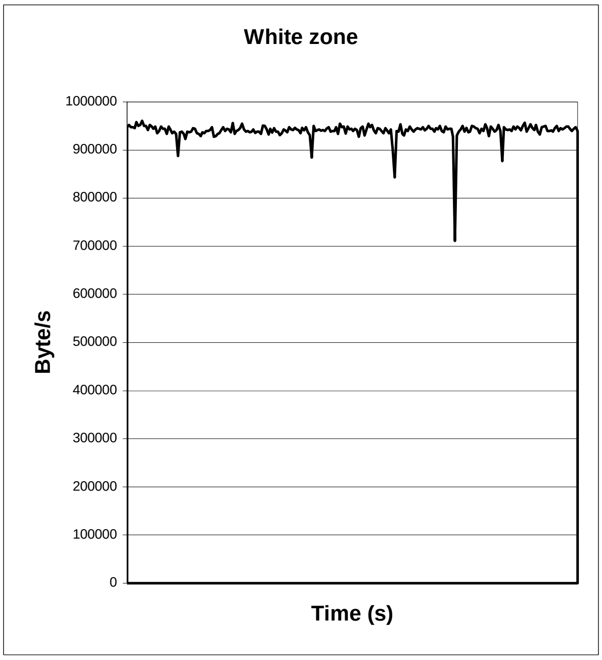


Figure 2: White zone

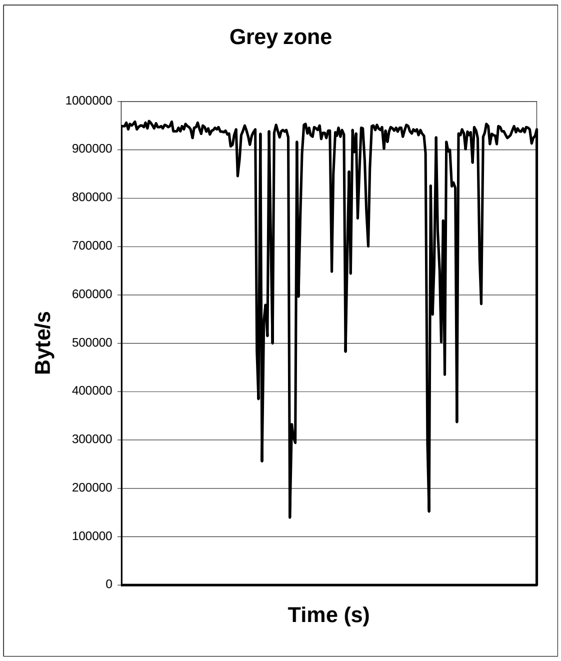


Figure 3: Grey zone (1)

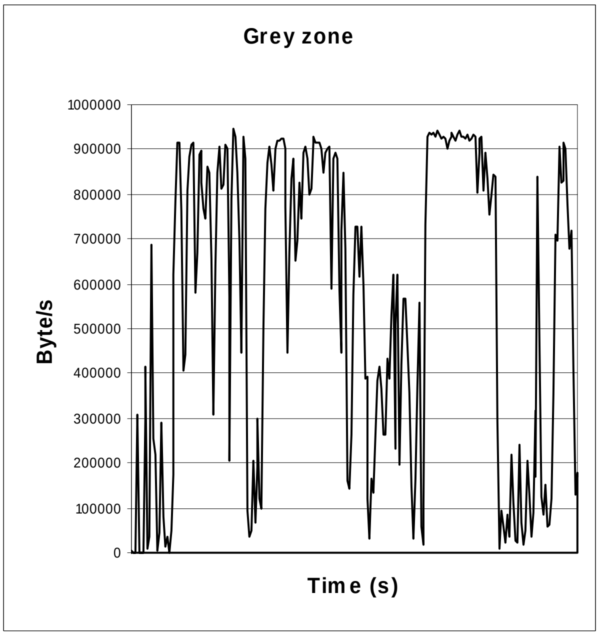


Figure 4: Grey zone (2)

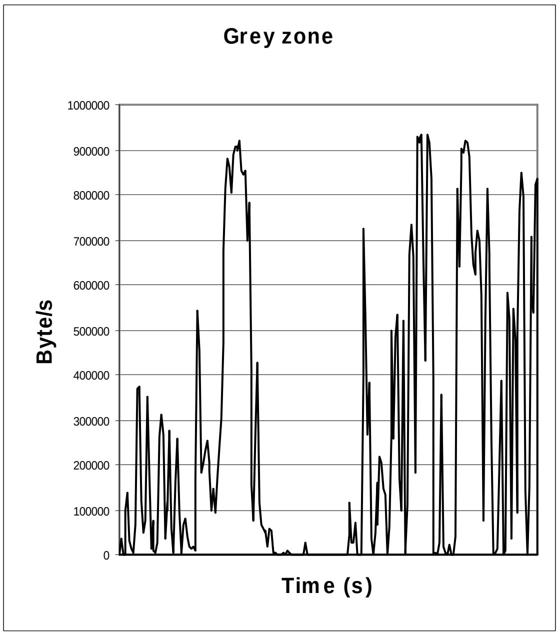


Figure 5: Grey zone (3)

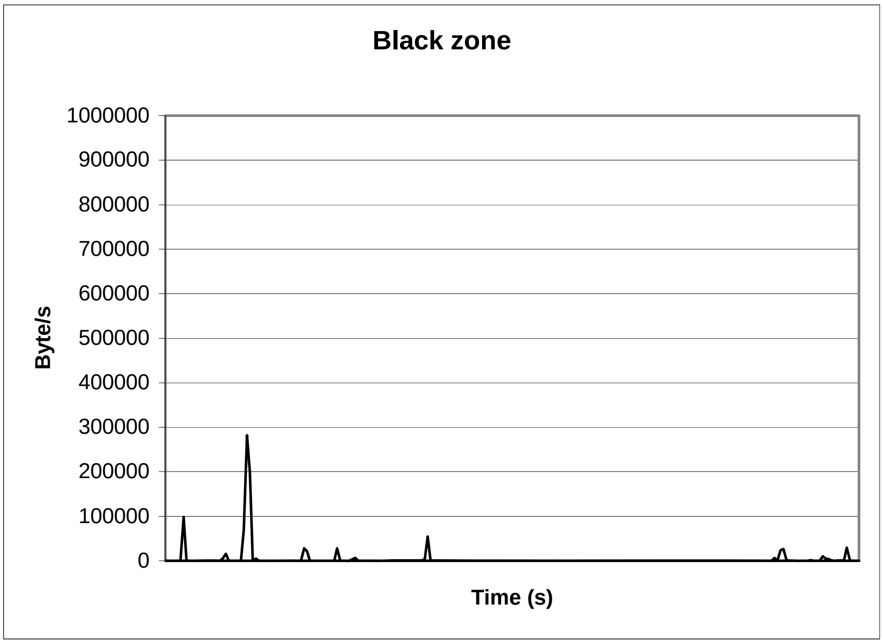


Figure 6: Black zone

The measurements shown above have been performed with different types of terrain. While the different terrain types did affect the size of the black and grey zones, the basic propagation characteristics did remain the same. However, the absolute size of the white and grey zones were not the same for different terrains, even if the type of the terrain (woods with brushwood, for example), did remain the same. The beginning of the grey zone is indicated by minor oscillations that are showing up (see Figure 3), and these oscillations become more significant with increasing distance to the sender (see Figure 4 & Figure 5).

4.3. Conclusion

It is not possible to determine generic fixed values for the sizes of the grey and white zones of a specific type of terrain. The absolute sizes of these areas depend on the propagation characteristics specific location and cannot be predicted with a reasonable accuracy. The absolute sizes of these zones do also depend on the orientation of the nodes antennas and, to a minor extend, on the size of the transmitted packets. So absolute data, regarding the size of the white zones and grey zones from measurements, can only be used for simulating a specific terrain, not a terrain type. In some cases, our collected measurement data from similar environments resulted in very different propagation characteristics.

Although our experiments did show that it is not possible to predict the radio propagation for a specific terrain, it is possible to create realistic radio propagation models that can be used to evaluate the performance of wireless networks. The different environments basically just differ in the size of the white and grey zones, while, if absolute sizes are disregarded, the general appearance of the grey zone remains the same.

5. Propagation model

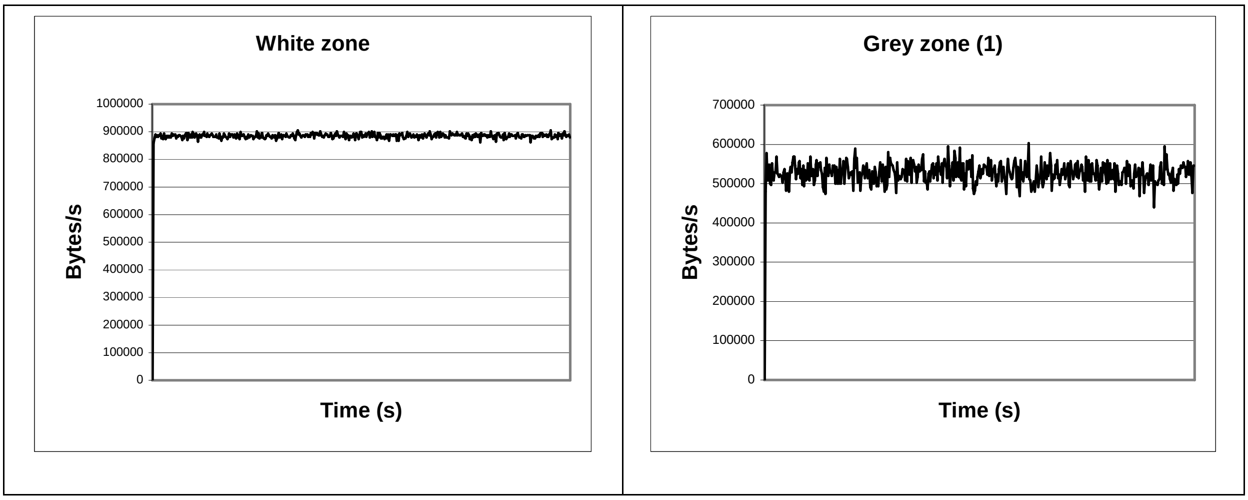
For performing accurate simulations, a detailed model of the physical layer is required. We decided to survey available radio propagation models for ns-2 with respect to the possibility of modelling realistic radio propagation. Our focus was on the possibility of modelling grey zones and on the possibility of defining a methodology for simulating ad-hoc networks in different, realistic environments. Although our observations with our experiments did show that it is not possible to create a generic single propagation model that simulates any terrain or a specific terrain type, it should be possible to create propagation models that simulate a set of realistic terrain types by creating propagation models with differently sized grey and white zones. Since the size of these two zones is, according to our measured data, the only variable in radio propagation, realistic simulations should be possible, to a certain extend, with a propagation model that correctly simulates these zones.

Currently, there are four propagation models available for common network simulators:

- The free-space model
- The two-ray-ground propagation model
- The shadowing propagation model
- The Ricean/Raleigh fading propagation model

The first three models model the large scale fading, while the Ricean/Raleigh fading models small scale fading and needs to be combined with one of the other models to form a complete propagation model. The free-space and two-ray-ground models are deterministic models, not capable of modelling grey zones at all. So our detailed survey did concentrate on the Ricean/Raleigh and on the shadowing propagation model.

The shadowing propagation model is capable of modelling different terrain types and also grey zones of different size. The model can be parameterized to reflect different terrain types. However, it was not possible to create the large-scale oscillations that we did observe in our experiments (see Figure 4 for example). Figure 7 gives an example of the radio propagation with the shadowing model.



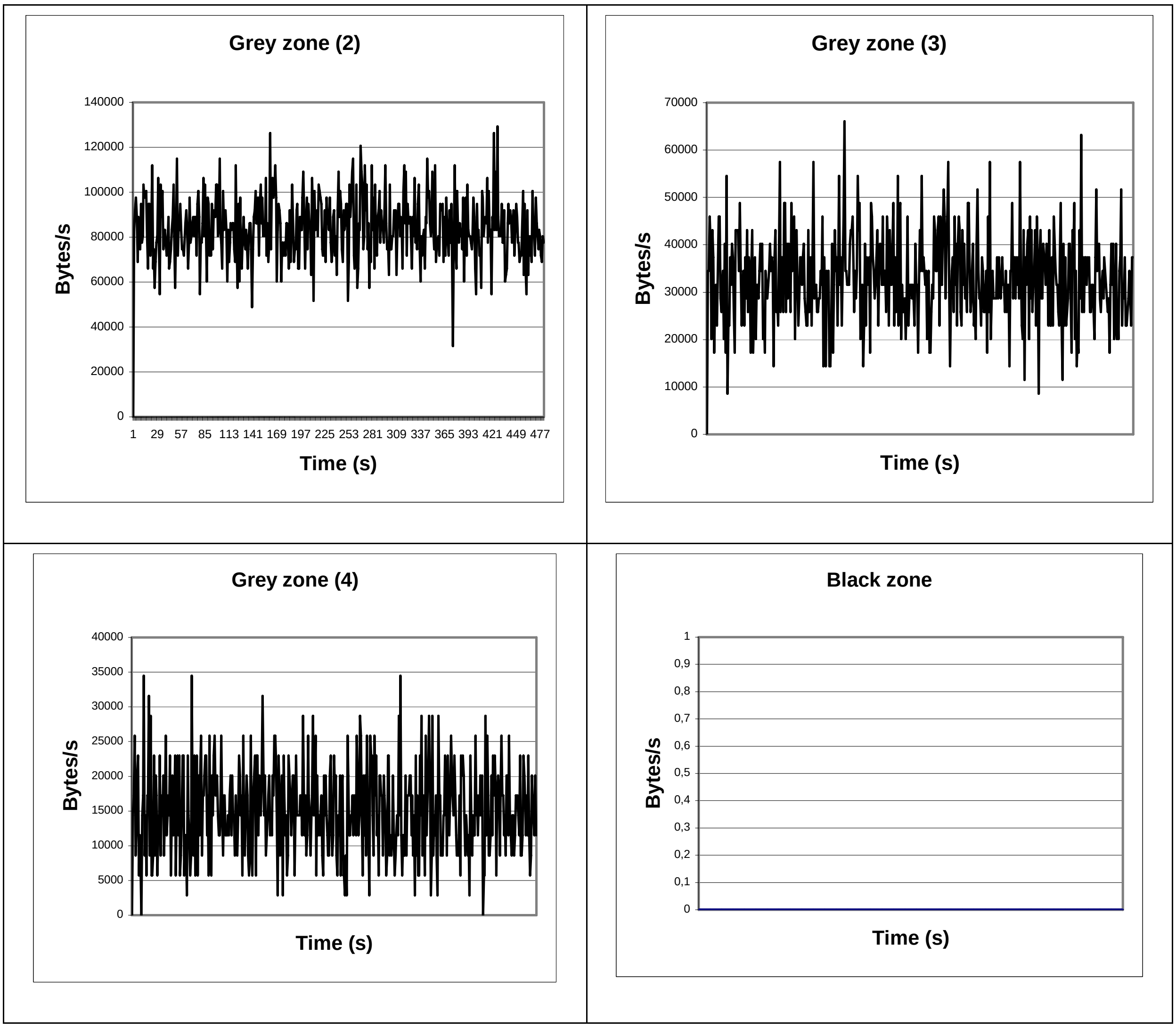


Figure 7: Simulation with shadowing propagation model

As it can be seen above, it is not possible to accurately model the oscillations in the transmission quality. The received signal strength of the shadowing model degrades much more gracefully than it would in reality. So we decided to combine the Ricean/Raleigh and the shadowing model.

Basically two effects of the reality have to be simulated in a realistic simulation: The large scale fading that originates from obstacles and from the distance between the transmitter and the receiver node and the small scale fading that mainly originates from interferences. The models that shipped with *ns-2*, including the shadowing model, were only capable of modelling large scale fading. So we decided to combine the Ricean and Raleigh fading that was presented in [PNS00] with the already available shadowing model. While the shadowing model simulates large scale fading and grey zones, the Ricean and Raleigh fading is capable of simulation high frequent oscillations. Both models combined can be customized with numerous parameters to reflect a special environment. Figure 8 shows the results of our parameterization.

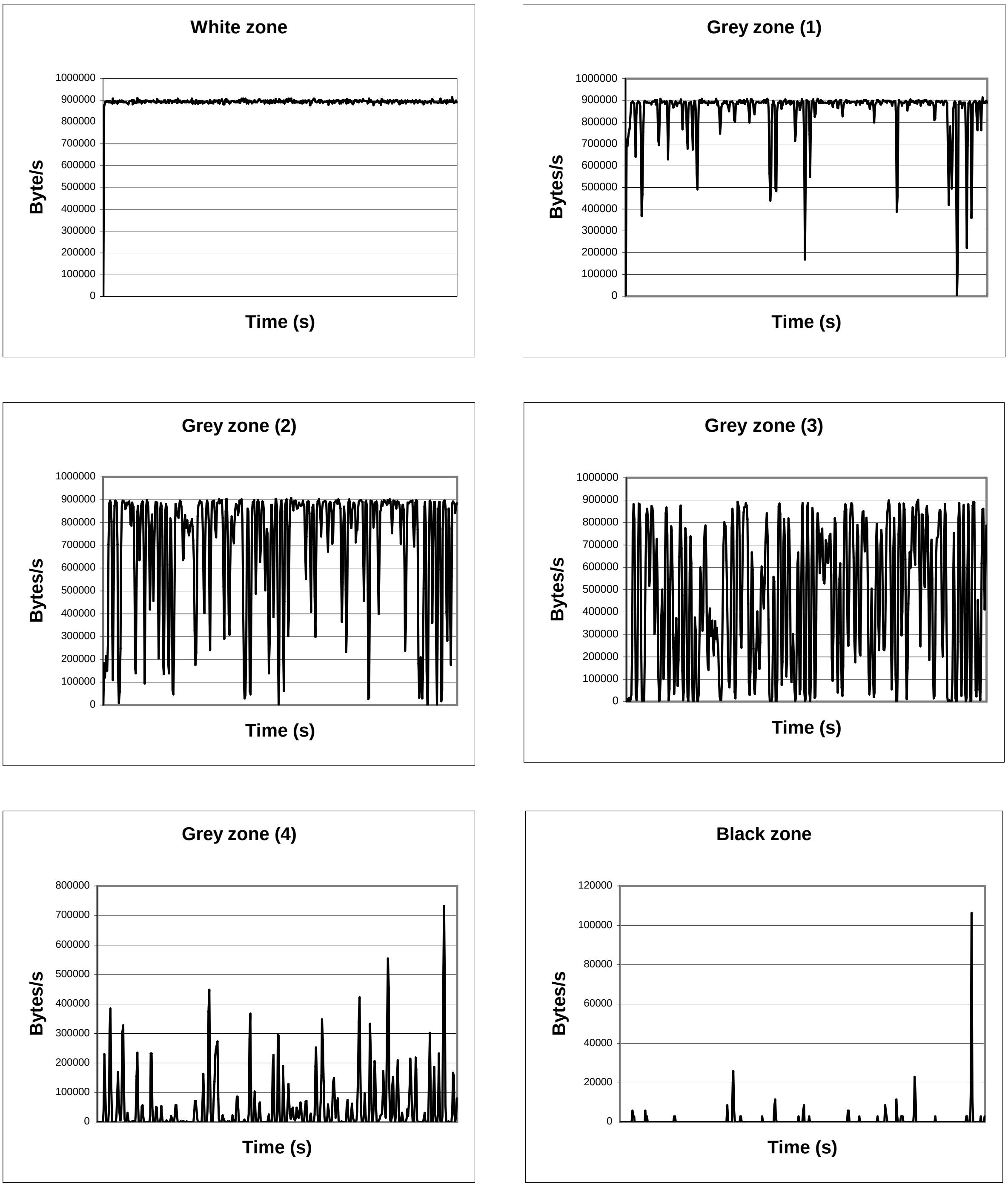


Figure 8: Simulation with Ricean/Raleigh fading

As it can be seen, the Ricean and Raleigh fading is, with correct parameterization much more accurate than the shadowing model. The shadowing model is unable to simulate the large oscillations in the grey zone accurately – it is not possible to model low frequency oscillations with the shadowing model as sole propagation model. Instead, the transmissions decrease with the shadowing model more gracefully – although it does oscillate to a certain extend. The amount of inaccuracy that might be introduced in certain simulation studies due to this unrealistic, graceful degradation is an area of our current research. The next Section compares simulation results from a realistic routing protocol [FG05] using a simplistic propagation model – the two-ray ground model with simulation results from using our realistic propagation model.

6. Simulation studies

In this Section, the performance of a multihop routing protocol is evaluated. The simulated routing protocol is NXP/MPR [FG05], a selective flooding that is used for routing broadcast messages through a wireless network.

Two simulation studies were conducted – one with a simple two-ray ground model that is not capable of modelling grey zones and one with our realistic radio propagation model. In the simulated scenario, ten nodes are lined up with a certain distance between them. Node 1 starts transmitting messages and all other nodes count the received and forwarded messages. The messages that are received by node number 10 indicate the amount of messages that were correctly transferred through the multi-hop network. Table 1 compares the results of these two simulations.

	Simple propagation model		**Our propagation model**	
Node ID	% Received	% Forwarded	% Received	% Forwarded
Node 2	100,0%	0,0%	99,99%	5,99%
Node 3	100,0%	100,0%	17,80%	17,64%
Node 4	100,0%	3,1%	17,75%	7,11%
Node 5	100,0%	100,0%	17,42%	16,61%
Node 6	100,0%	3,1%	17,07%	9,44%
Node 7	100,0%	100,0%	16,67%	14,71%
Node 8	100,0%	100,0%	15,98%	15,81%
Node 9	99,9%	0,0%	15,94%	13,23%
Node 10	99,9%	0,0%	15,74%	7,66%

Table 1: Comparison of protocol performance with different propagation models

As it can be seen in Table 1, the simplistic propagation model yields in a much better performance of the routing protocol that our realistic model. The number of received packets at the last node is significantly higher, with 99,9% nearly all transmitted packets are received at this node. It can also be seen, that the algorithm corrects detects those nodes that are required as packet forwarders. Our more realistic model causes the performance of NXP/MPR to decrease significantly. The problems of NXP/MPR with realistic propagation models originate from its detection of the transmission range of a node. The simulation study with the realistic propagation model did reveal that the range detection is not yet able to handle grey zones. Grey zones appear in every real wireless LAN network, so this would have lead to many unexpected errors during testing on real hardware. Even worse, the absence of grey zones in simulations could void simulation results when routing protocols are evaluated. The grey zone detection is likely to introduce some additional overhead into the routing protocol. This results in a lower performance of a grey zone aware protocol when it is being compared by using a simplistic propagation model. In reality, the grey-zone aware protocol will perform much better, making the simulation results for accurate evaluation unusable.

So using realistic propagation models is important, even if only protocols at higher protocol layers are simulated and evaluated. Changing the default propagation model to a more realistic one will affect the performance of all protocol layers up to the simulated application.

7. Conclusions

We did show that the used radio propagation model has a severe impact on the results of simulation studies. This does not only affect protocols on the lower layers of a protocol stack, but also routing- and application level protocols. Also the effect of grey zones is underestimated in many simulation studies. This leads to the usage of over simplistic radio propagation models that model the reality inadequately. The results of these simulation studies are questionable. Since grey zones exist in reality, it is imperative to use radio propagation models for protocol validation that can simulate the effects resulting from these zones. Otherwise, the simulations will probably hide a great deficit of protocols that cannot cope with grey zones.

Although, due to many unpredictable factors it is not possible to predict the radio propagation for a specific terrain, it is possible to create realistic radio propagation models that model common terrain types. Since most of the currently used ad-hoc networks are mobile networks, the radio propagation of their environment is likely to change during their uptime, making a performance study that reflects multiple types of terrain feasible.

We did also show that the propagation area surrounding a node can be divided into five areas of different connectivity. Depending on the propagation characteristics of the specific terrain, the size of every area may be larger and smaller. We did also show, that the connectivity starts oscillating the farer away the receiver is located from the sender. Most simplistic models are not able to simulate these oscillations; they simulate instead a constant connectivity at the mean connectivity level.

For achieving a comparable and realistic protocol performance prediction, the protocol must be simulated using realistic radio propagation models. This ensures that also effects the effects of grey zones, and the effects of the observed oscillations are considered in the performance evaluation. Our realistic propagation model shows that it is possible to create radio propagation models that model the reality to a sufficient accuracy level. Since this topic is ongoing work, the following Section documents research areas that are still open. Our main research goal in this area is to assess and to evaluate the error that is introduced by different radio propagation models with different characteristics and to provide a methodology for performing realistic simulations of the physical layer of wireless networks.

8. Further work

Although our created radio propagation models are capable of accurately simulating environmental factors, the size of a transmitted packet is still not considered. This will require a second run of experiments. Also the formal classification of measurement data into transmission areas is an issue that is being worked on. This would enable us to formally define the size of every transmission area.

The impact on simulation accuracy of other physical effects, namely collisions that may occur, need also to be evaluated. Although the *ns*-2 is capable of simulating collisions and capturing, there is very little work on the realism of this simulation component.

The observed oscillations in measured connectivity should also be evaluated with respect to their effects on the operation of common routing protocols. Since the commonly used simplistic propagation models are not capable of modelling these oscillations, probably the performance of current routing protocols needs to be re-assessed.

Our measurements did show that the identified propagation areas only differ in their size. For all environments, all of these areas have been visible, although they did span an area of different size for the specific environments. Probably it would be possible to develop a propagation model that could be used for modelling generic, yet realistic environments. Maybe this could be achieved by making the size of the five propagation areas configurable.

Another further research topic is the portability of these radio propagation models. Their suitability and adaptability to other transmission techniques operating in the 2,4 GHz frequency band is an interesting research topic, also with respect to the growing research area of sensor networks that also require accurate simulations.

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