Building a Better Wireless Mousetrap: Need for More Realism in Simulations

Matthias Wellens, Marina Petrova, Janne Riihijärvi, Petri Mähönen

Aachen University, Department of Wireless Networks, Kackertstrasse 9, 52072 Aachen, Germany
E-mail: mwe@mobnets.rwth-aachen.de

Abstract

Reliable network simulators are important tools for research and development in the field of wireless communication. Although the ns-2 simulator is quite popular for testing wireless network protocols in industry and academia, it is more than clear that it needs numerous improvements in order to produce results fitting to realistic scenarios. There are many PHY/MAC modelling parameters that contribute to the overall accuracy but are not taken into account in the current ns-2 versions. In this paper we stress out the importance of adaptive error models, propagation and mobility models and better interference calculation. We propose a SNIR-based error model in order to reliably simulate the behaviour of the wireless channel and facilitate more realistic results of WLAN simulations. The results proove that our extensions are suitable and allow precise simulations of static WLAN scenarios.

1 Introduction

Accurate simulation tools are often necessary requirement to estimate and measure the feasibility and the effectiveness of any new research idea. However, simulating complex networks is not a trivial task [7]. In the past couple of years the ns-2 simulator [1] has become a commonly used tool to test wireless networks (especially IEEE 802.11 based WLANs) both in industry and academia. Performing simulation is quite useful way of studying the wireless protocols and the network behaviour especially when building analytical models turns out to be complicated. Although the ns-2 simulator is popular in the networking community it is more than clear that it needs a number of refinements and extensions in order to produce results that fit to realistic scenarios. Most of the constraints to get reliable simulation environment arise from the simplicity of the IEEE 802.11 implementation. In this paper we mainly address the implementation of the PHY/MAC model of 802.11 in ns-2 and give some insights into the causes of the unreliable results when simulating the performance of the wireless networks. We stress out the importance of more flexible and accurate error models, propagation and mobility models and better interference calculation for overcoming the limitations of and scepticism towards many results obtained from simulations.

It is of critical importance to simulate and process the lower OSI-level phenomena right in order to produce reliable results for high-layer studies. Thus,

we also believe that, e.g. ad hoc routing, service discovery, and mobile computing studies (just to name few) would benefit from enhanced wireless simulation capabilities. Naturally, these improvements are important overall, but showing differences, e.g., in jitter and ad hoc routing performance is left for a later specific paper, as we concentrate here on describing lower-layer simulation aspects.

There are many PHY/MAC issues or say, modelling parameters that contribute to the overall accuracy of the simulated environment that are not taken into account in the current ns-2 versions. Just as an example, in this context we can note that ns-2 is unable to simulate co-channel and co-system interference and does not include the background noise when calculating the SNIR which leads to more optimistic estimation of the channel conditions.

In this paper we propose SNIR-based error models, which dynamically adapt to the channel conditions. During the analyses we considered Bernoulli-, Gilbert-Elliot and chaotic map error models. These were configured using measurement traces taken in a soft-partitioned office environment to ensure exact reproduction of the error statistics. In addition, we compared number of propagation models with the measured propagation characteristics of our environment and implemented the best-fitting one in ns-2. We show that our simulation framework with adaptive error model and improved PHY/MAC implementation simulates the behaviour of the wireless channel more realistically and corrects the too optimistic results of an unmodified ns-2.

The rest of the paper is structured as follows. Section 2 gives a brief overview of the relevant PHY/MAC implementation in ns-2. Section 3 covers some aspects of the SNIR

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calculation and its use as a parameter for introducing more flexible error models and better wireless channel modelling. Section 4 gives a theoretical insight to some commonly used error models. In section 5 a description and some results of the improved simulation environment are given. Further possible improvements and considerations in regard of our work are presented in section 6. Finally we conclude the paper in section 7.

2 Description of the current PHY/MAC implementation in ns-2

In ns-2 the most important criterion during the frame reception process is the received power P_r. A propagation model calculates P_r based on the transmission power and the distance between the communicating nodes. Most studies have used either the *FreeSpace* or the *TwoRayGround* propagation model. The former one is based on the assumption of wave propagation in an environment without any obstacles. The latter one considers a second wave reflected from the ground if the distance is larger than *crossover-distance*. WLAN frequencies in the 2.4 GHz band lead to a crossover-distance of about 230 m.

Additionally, ns-2 supports a statistical shadowing propagation model. A random number from log-normal distribution is added in order to calculate P_r. As a result P_r at a certain distance is not a fixed value anymore, the communication range varies, and the probability to receive a frame successfully will go down if the distance between transmitter and receiver increases. The random variable is independent of the actual channel conditions and its statistics can be configured to model different types of topologies. This is a relatively good way to build statistical models without using, e.g., complex raytracing with topological maps. However, the choice of parameters is crucial.

In order to decide whether a frame reception was successful P_r is compared to two different thresholds: *CSThresh* (Carrier Sense threshold) and *RXThresh* (Receive threshold). If $P_r <$ *CSThresh* the node will not consider the received frame anymore because it is below its sensitivity. A possible collision of such a frame with another frame will be neglected. If *CSThresh* $\leq P_r <$ *RXThresh* the node will start the reception process and the medium will be sensed as busy during the respective transmission time. However, the node will directly mark the frame as received erroneously because P_r is too low. Finally, a frame with *RXThresh* $\leq P_r$ can be received successfully if no collision occurs.

Collisions of two different MAC-frames are modelled by comparing the ratio of received power P_r and interfering power P_i to a third threshold, *CPThresh* (Capture threshold). If $P_r/P_i <$ *CPThresh* the receiving process will fail because of a frame collision. For the calculation of the mentioned ratio always only one interfering frame is considered. Therefore, neither cumulative interference (interfering power from more than one neighbouring source) nor thermal noise are taken into account.

The default values of the mentioned thresholds and the transmission power are based on a Lucent WaveLan device working at 914 MHz. Together with the FreeSpace and TwoRayGround propagation models these thresholds result in a communication range of more than 200 m. However, it will be difficult to determine precise thresholds even if we consider today's IEEE 802.11 products because the hardware characteristics from different vendors vary considerably.

In addition to the trivial reception process ns-2 offers basic error models. A uniform error rate and some simple approaches such as periodic errors or a predefined error trace are included. Besides, a multi-state error model is also available and can be used to implement the Gilbert-Elliot error model. However, the standard distribution of ns-2 does not include default parameters for these models to configure a WLAN simulation. Further on, the channel conditions or the frame size do not influence the error model since it is implemented as an independent process.

Another important part of network simulation is mobility. Ns-2 does not consider such models during simulation runtime. Instead, an interface to use separate files describing the movement of the nodes is offered. Therefore, no dynamic interaction between the mobility and the rest of the simulation is possible.

Ns-2 offers a tool to precalculate mobility traces based on random waypoints. For those seeking to use different models, several mobility generators are available as separate extensions. One of the more powerful ones is the CANU MobiSim suite [3], developed at the University of Stuttgart. In addition to several "traditional" mobility models, the CANU suite implements a rather flexible meta-model for setting up complicated mobility scenario. The meta-model itself is described in detail in [23]. The mobility scenarios generated can be used for simulations in ns-2, and also in a number of other simulators.

An interesting toolkit from the University of Bonn is described in [5]. This software suite includes a mobility scenario generator, and also an analysis tool to study the behaviour of the model graph characteristics. Exporting to ns-2 is supported.

The tools developed by the IMPORTANT project are available at the project website [25]. Presently this includes the mobility generator, with the analysis tools soon to come. The generated traces are compatible with the ns-2 simulator.

3 Impact of SNIR

In most performance studies of wireless networks the throughput is one of the parameters that is usually simulated and used to verify new concepts. It primarily depends on the effectiveness of the source to acquire the wireless channel and on the Signal-to-Noise-and-Interference Ratio (SNIR) at the receiver side. During propagation the wireless signal suffers from various degradation effects such as fading, shadowing and path loss. Additionally the mobility of the node causes variation of the signal power in time. Taking all these into account, the probability of correctly received frame will depend on the ratio of its signal power to the overall noise and interference power received from the environment. As mentioned in the previous section ns-2 decides if the frame is successfully received or not based on received power. The system will accept the current frame as correctly received only if its power at the receiver side is above the receiving threshold *RXThresh*. This reception criterion takes into account only the path attenuation that the frame can experience from the sender to the receiver. High enough receiving power does not necessarily mean frame without errors in a real setup. If the success of a frame reception is based on the simulated SNIR some further effects such as the interference can easily have a significant impact on the reception performance. In this case the thermal noise and the noise from several other sources in the surrounding may increase the interference level, lower the SNIR, and endanger the correct reception of the frame. As a result the cumulative interference will be an important aspect especially if the simulated network becomes more crowded. In [24] the PHY-layer implementations of several network simulators were compared. The lack of cumulative interference simulation was determined as a clear disadvantage of ns-2 that results in too optimistic results.

4 Error models

If static topologies or scenarios with slow mobility need to be analysed in system level simulations, usually effects such as fast fading or multipath propagation will not be modelled in detail. Instead, stochastic error models are used to simulate errors at the receiver. One simple way is to define an average frame error rate (FER) and use independent errors (Bernoulli-Model). This is a memoryless process, which means that the output value at each iteration is independent of the previous outputs. The most used approach is the Gilbert-Elliot error model based on a two-state Markov chain [6, 8], that can reproduce burst errors.

For closer representation of real systems, error models are often configured using measurement results [27]. In this case the parameters of the error model, e.g. state transition probabilities, are calculated from the measured error traces. Such configured error models can be used to produce artificial error traces.

In order to analyse the accuracy of error models and estimate how closely the measured data can be reproduced, *runs* and *bursts* are introduced. A run corresponds to numerous consecutive frames that are received without any error. A burst is a sequence of corrupted frames, respectively. Besides the average FER, which is the most important value, several higher order statistic factors such as the distribution of the run or burst lengths have to be reproduced accurately.

As a first step we compared measured error traces taken in good channel conditions with simulated traces of Bernoulli-, Gilbert-Elliot, and chaotic map error model. The Gilbert-Elliot error model, originally developed to model fixed networks, and the two other models reach an accurate enough reproduction. The chaotic map error model is based on an equation introduced in chaos theory and was proposed as an error model for wireless systems in [14].

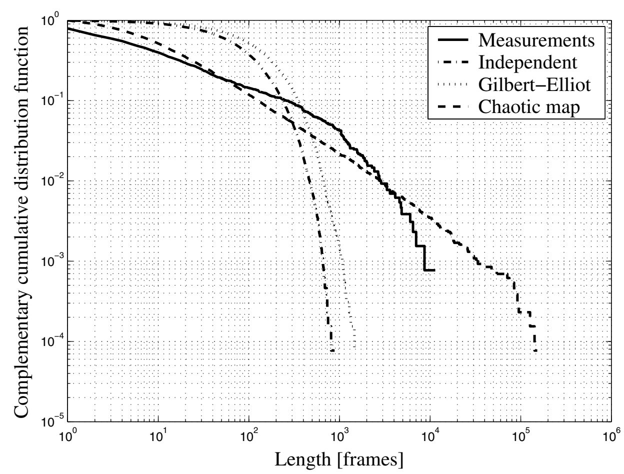

Figure 1. Example for the run length distribution in bad channel conditions.

Figure 1 shows the run length distribution in bad channel conditions. The resulting distribution is heavy-tailed, which often occurs under such conditions. The Gilbert-Elliot error model is not anymore able to reproduce the run length distribution as it always results in a geometric distribution. On the other hand, the chaotic map error model is also able to reproduce the heavy-tailed distribution.

Several research papers have analyzed the run and burst length distributions and propose error models that reach a better reproduction. Nguyen *et al.* suggested in [21] to divide the measured distribution into several parts based on the lengths of runs and bursts. Shorter runs are modelled using Pareto distribution whereas longer runs and bursts using exponential distribution. A Markov model will be more accurate if the number of states is increased. The bipartite model, presented in [26], reaches a very good reproduction of the measured distributions but needs a very large number of states and is very complex. Konrad *et al.* found out in [12, 13] that too long runs cause a loss of stationarity and Markov models cannot reproduce non-stationary processes. They introduced a state hierarchy and used one completely *error-free* and one *lossy* state on the first level with exponentially distributed state holding times. The lossy state on this part is modelled by a certain number of second level states. The state transition between these can be modelled using a Markov model because the non-stationary parts of the measurement trace are covered by the error-free state.

Generally, there are mainly bit-based or frame-based error models. Also time or block-based models can be found in the literature [19]. During our studies we concentrated on frame based error models because 802.11 WLANs are completely frame based systems. The most widespread standard 802.11b does not implement Forward Error Correction (FEC). Therefore, the number of bit errors and their position within a single frame are not important as a node will drop a frame already because of a single bit error. Additionally, the characteristics of the run and burst length distributions of bit- and frame-based measurements are similar so that bit-based models can also be deployed as frame-based ones. For example in [14] the chaotic map was proposed only as a bit-based model, but we show in figure 1 that it is also applicable as a frame-based model.

5 Implemented extensions

5.1 Improvements

As described in section 3 the performance of a real receiver mainly depends on the values of the SNIR during the reception. Our measurements show that the run and burst length distributions also clearly depend on the channel conditions. Therefore, a realistic and flexible error model should also take those into consideration. Additionally, we remind that the probability to receive a frame successfully depends to a certain degree on its size. Although today's WLAN receivers implement sophisticated channel estimation algorithms the error probability for longer frames is still higher.

In order to increase the level of modelling accuracy in ns-2 we implemented error models based on independent errors, on the Gilbert-Elliot model and on the chaotic map. Furthermore we extended the simulation environment to track the SNIR at every node during the complete simulation time. The interference level is calculated from the thermal noise and received power of all colliding frames and afterwards compared to P_r. The framesize and the worst SNIR during a frame reception are used to select a certain *Parameter Set*. This Parameter Set contains all needed variables of the error model besides the model state itself. For example a Gilbert-Elliot Parameter Set consists of the error and the respective state transition probabilities. If the channel conditions and thus the SNIR change, the state of the error model will not be changed so that a burst may continue but the respective model parameters are adapted. SNIR-based error models have already been considered in some network simulation studies [19]. However, in these cases a certain SNIR was set for the whole simulation instead of implementing a flexible error model that adapts to the actual SNIR.

In order to extract Parameter Sets for different channel conditions we took extensive measurements with off-the-shelf 802.11b hardware in a soft-partitioned office environment. Furthermore we used the measurement results for comparison to existing propagation models and to configure a more precise one. As described in section 2 the current ns-2 model for 802.11 systems calculates a communication range to be more than 200 m, which is clearly too much in most cases. Figure 2 shows the output of our measurements and results of some published propagation models. The TwoRayGround model is not shown because the measured distances are below the mentioned crossover-distance. *VariableGamma* is based on a FreeSpace propagation model but uses a higher attenuation factor $\gamma = 2.6$. Having the comparison graph for several propagation models, finally we chose the *CombinedGamma* model [10] as it is based on measurements with 802.11b hardware and fits our measurements well. Together with the newly implemented error model it results in a communication range of about 30 m.

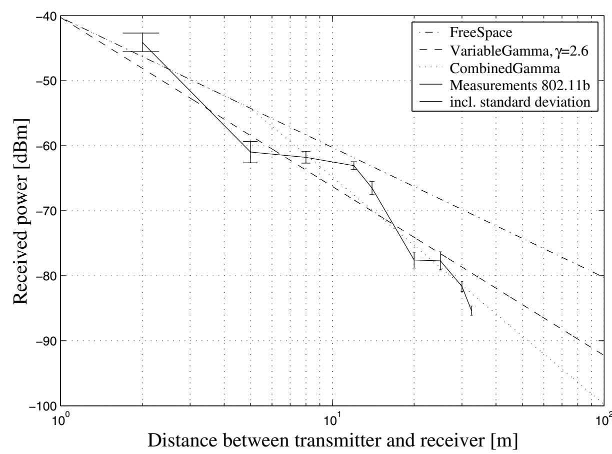

Figure 2. Radio propagation measurements with IEEE 802.11b.

5.2 Results

In order to compare the basic ns-2 and the improved simulation environment two simple scenarios were used. For all simulations the new propagation model was adopted. Additionally, the ns-2 patch in [16] was used to avoid some mistakes in the MAC-layer implementation of IEEE 802.11b systems. The main changes compared to the basic ns-2 are support of the short frame format, support of higher transmission speeds for acknowledgements, implementation of the Clear Channel Assessment-process (CCA), support of different PHY types, and several minor improvements in the implementation of interframe spaces. During the comparison the following simulators were used:

- Completely unmodified ns-2 v2.26.
- Ns-2 v2.26 including only the patch [16].
- Ns-2 v2.26 including the patch and using a newly implemented error model (Gilbert-Elliot or chaotic map).

Figure 3 shows the simulated TCP throughput over time of a single IEEE 802.11b connection. The receiving node recedes from the transmitter and therefore the channel conditions become progressively worse. The patched ns-2 without an improved error model does not simulate this effect at all. The connection breaks when the moving node reaches the edge of the communication range. The simulation results of the improved ns-2 environment lead to more realistic behaviour because the throughput decreases slower and the variance increases when the channel conditions become worse.

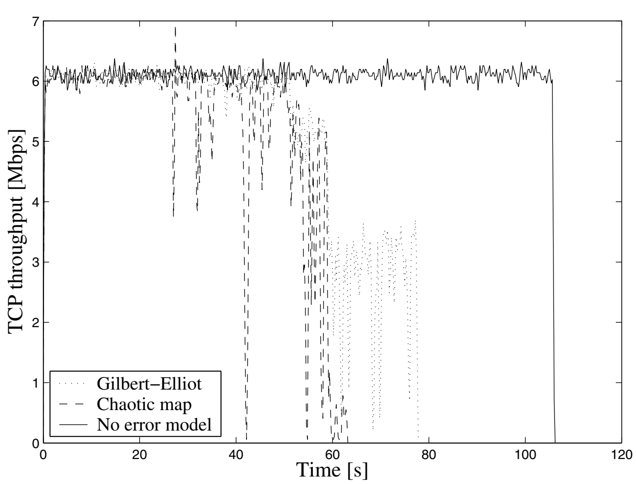

Figure 3. Importance of the consideration of the channel conditions in an error model.

Table 1 lists the simulation results of a single UDP connection between two 802.11b devices. As the channel conditions are very good the fastest available PHY-rate of 11 Mbps is used. The throughput simulated with

UDP datagram size	556 bytes	1004 bytes	1480 bytes
Gilbert-Elliot [Mbps]	4.33	5.95	6.98
No error model [Mbps]	4.34	5.96	7.00
Theoretical [Mbps]	4.34	5.96	7.00
Unmodified ns-2 [Mbps]	3.66	5.18	6.24

Table 1. Maximum reached UDP throughput.

Gilbert-Elliot error model is slightly lower than the theoretical value. This result is reasonable because in a real system few transmission errors will also occur. Additionally, it was shown that the Gilbert-Elliot error model reproduces good channel conditions very well.

The theoretical value, which was derived in [17], matches the simulation result without an error model and thus proves the accuracy of the MAC-implementation. The completely unmodified ns-2 clearly results in too low numbers which are mainly caused by the missing support for the short frame format and the oversimplified PHY-implementation. It must be pointed out that the simulation accuracy for other performance parameters such as bit rate variance, jitter, or coverage will also benefit from the improved simulation environment. The UDP throughput was chosen to concentrate on a simple but representative example.

6 Future challenges in network simulation

The above-described simulation environment is suitable for rather small static and homogeneous scenarios. Introducing mobility and heterogeneous technologies in the wireless scenario will require a variety of mobility models, consideration of fading and Doppler-spread, and the calculation of co-channel and co-system interference in ns-2. In this section we give an overview on some of these aspects.

6.1 Mobility models

To illustrate the problems that can surface due to the selection of the mobility models, we shall shortly recall two of the most basic mobility models as known from the literature. For a thorough review of various mobility models, the reader is recommended to study the well-known review [2], which also includes numerous references on the impact that mobility models can have on the performance of ad hoc routing protocols.

Brownian motion The Brownian motion and its variants, usually referred to under the collective name of "random walks", form the family of mobility models with undoubtedly the longest ancestry. The most common form of the random walk is obtained by repeating the following two steps on a plane: (1) Select random speed uniformly from interval $[v_{\min}, v_{\max}]$, and a random direction uniformly from $[0, 2\pi)$. (2) Proceed with the speed and direction obtained in the previous step for a constant time t.

Occasionally a variant is used, where the same direction and speed is maintained for a fixed *distance*, instead of fixed time. If simulation is to be performed in a spatially bounded area, boundary conditions must be specified. Typically the boundary is assumed to cause a reflection of the trajectory as of a light ray from a mirror.

Random waypoint models Due to the numerous shortcomings of the Brownian motion -model, several alternatives have been proposed. The most commonly implemented (and accordingly very commonly used) of these appears to be the random waypoint model introduced in [11]. This is the only real mobility model supplied in the default ns-2 distribution.

Compared to the Brownian motion, the random waypoint model, as commonly defined, introduces two changes. First one is the selection of destination point uniformly from the simulation area, instead of choosing a direction at random. Second is the introduction of a constant *pause time*, which the nodes spend immobile after reaching their destinations. The travel between successive destinations is done linearly, at a constant speed obtained similarly from a uniform distribution as in the random walk case.

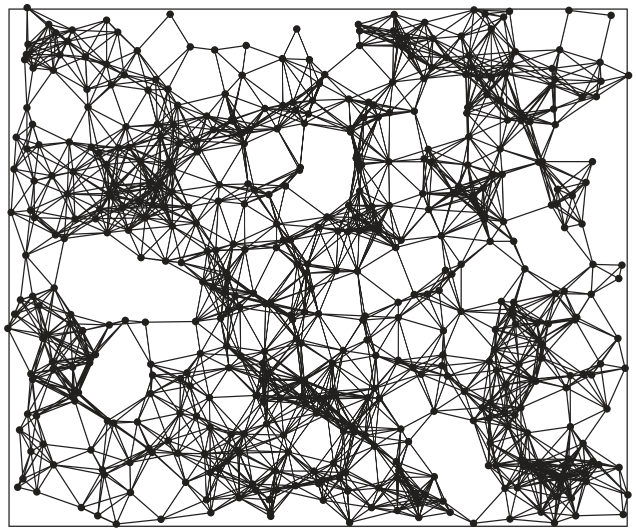

Figure 4. Ad hoc network topology when the random walk model is used.

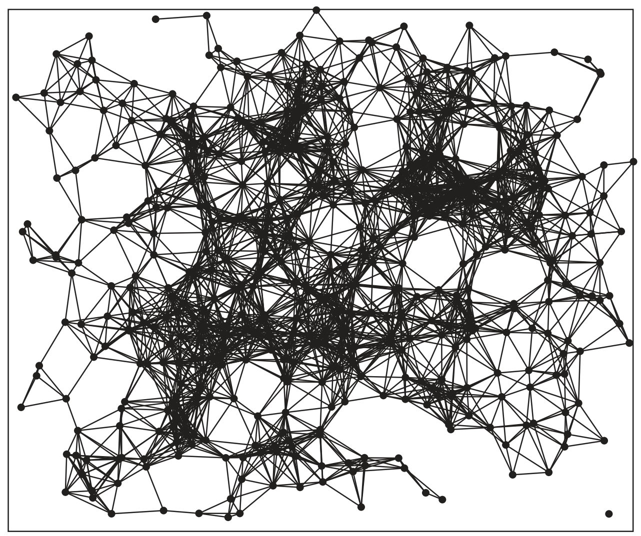

Figure 5. Ad hoc network topology using the random waypoint model.

6.2 Impact of choosing the mobility model

The two simple models presented are already sufficient to illustrate the dramatic differences in perceived network operation that can result. From figure 5 we see even quantitatively that the density of the simulated ad hoc network is higher at the center of the simulation area. Contrasting this with the case of a simple random walk simulation illustrated in figure 4, we see that the node distribution has remained far more uniform. Thus the selection between these two models would result in highly different load distributions, with even more dramatic differences if instead of ad hoc networks we would consider access points distributed evenly on the simulation area. Further differences would arise if we were to study handover frequencies between the access points. Random walks tend to stay localised near their original points with a wide variety of parameters, while random waypoint model leads to nodes travelling longer distances from their origins more often.

Numerous novel mobility models have been constructed to take into account the constraints placed on mobility in real life by buildings, vegetation and so on. However, many of the suggestions require use of a combination of external programs and hand-made obstruction topologies. For generic network simulation a solution of this kind is not acceptable. Instead, a statistically correct, parametrised model integrated into ns-2 should be adopted. Such a detailed mobility model should enable simulation of further effects such as fast fading and Doppler-spread. One advantage of having the mobility model integrated into the ns-2 is, that it can use feedback information about the channel conditions. Hence, it could be beneficial to have better basic set of mobility models as a part of ns-2, but nevertheless integration between separate mobility model generators and ns-2 should be ensured. At present we are studying the use of graph-generation techniques (see, for example [20]), coupled with graph visualisation algorithms to automatically create the constraint graphs.

6.3 Co-channel and co-system interference, gray zone problem and rate adaptivity

The majority of the non-proprietary wireless networking products available today operate in the unlicensed 2.4 GHz and 5 GHz bands. As a result, in a real scenario these frequency ranges are open to interference coming from a variety of sources such as other 802.11, Bluetooth, or ZigBee devices. Both the WLAN and WPAN concepts embrace variety of technologies working in a same frequency band. Having IEEE 802.11b and Bluetooth in the same network will require consideration of the co-system interference for accurate calculation of the SNIR. Ns-2 is unable to simulate both co-channel and co-system interference. This is a serious handicap of the simulator since it cannot be used for performance analysis of simple wireless networks and testing algorithms for efficient frequency allocation. Including the interference factor in the criteria for a successful frame reception will help in more accurate simulation of wireless heterogeneous networks.

As the wireless systems become more widespread and the requirement for seamless wireless communication is getting stronger, an efficient channel allocation is becoming a necessity. Especially in dense hot spots and company networks the probability of interference and sub-optimal performance becomes higher. Proposals to optimize the frequency allocation of a WLAN by using *Colouring-algorithm* for effective channel allocation to WLAN access points already exist[18]. For further information the reader is referred to [9]. If the co-channel interference can be simulated in ns-2 more realistic simulation studies and capacity estimations will be possible.

Having adaptive error models as proposed in section 5.1 allow the simulation of additional features of a WLAN system. IEEE 802.11 is a multi-rate system, supporting raw data rates of up to 54 Mbps (in case of 802.11a/g). As a result, links can have many delivery rates. In this context, a link adaptation algorithm for automatic rate adaptation is very important for achieving better channel utilization and optimal throughput.

Several simulation-based studies of MANET routing protocols do not consider the effects of multi-rate networks and assume that all links are equal. In multi-rate networks this is far from reality. Moreover, the well-known "gray-zone" problem [15] is present because of differences in the communication range of the signalling and data packets. It is also well-known that the route selection based only on hop-count is clearly not optimal [4] for wireless networks. Thus it should be obvious that the evaluation and comparison of ad hoc routing protocols is very unreliable without realistic modelling capability discussed in this paper.

7 Conclusions

We certainly hope that discussion in this paper encourages more work towards providing better wireless simulation capabilities for ns-2, and other simulators. Our aim is not to discourage the use of any simulators or suggest that we should not trust simulations. But as Floyd and Paxson [7] have pointed out one should always critically evaluate the use of simulations. One should also be encouraged to be very careful on explaining all the assumptions and limitations that have gone in to simulation study, and in the case of wireless results a great care is required when results are interpreted. The requirement for interpretation and careful planning of simulation campaign is inevitable. In this paper we have tried to show some existing caveats that must be taken into account at least during the interpretation phase of research. Moreover, we have introduced some extensions we have developed in order to make simulations to resemble more reality, and to provide community better tool for WLAN and WPAN related research.

We would also like to point out against "oversimulating". For most of the general wireless network research, very complex models (e.g., having transceiver model with accurate parameters, topology of simulation domain, ray-tracing for propagation models) are not required, and could even be counter-productive and overly time consuming. Very accurate PHY-level models are, of course, required and one example is the study of cellular networks and coverage of those. But in many cases, we are interested in to adjust our simulation complexity just to the right level. Overly realistic simulations lead easily to problem that simulations become complex to analyze, very slow, and e.g. often we do not want to have detailed information on specific topology, but some sort of statistical average with reasonable error analysis.

The challenge is to build a reasonable simulation environment and guarantee that we understand what is done. As authors in [7] are so rightly warning, one should never mistake simulation for the real world. For this purpose we remind readers Oxford English Dictionary [22] definition for simulate: "1 a pretend to have or feel (an attribute or feeling). b pretend to be. 2 imitate or counterfeit". Only later the definitions include statement that simulate is also "imitate the conditions of (a situation etc.), e.g. for training. b produce a computer model of (a process)" and "(as simulated) made to resemble the real thing but not genuinely such". With this dictionary in mind warning we conclude emphasizing that we should simulate in order to resemble the real thing, but not confuse it with reality.

8 Acknowledgments

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