Low Resolution Radio Model for ns-3

Kirill Andreev
Telum
23 Trubnaya str.
Moscow, Russia 127051
andreev@telum.ru

Pavel Boyko
Telum
23 Trubnaya str.
Moscow, Russia 127051
boyko@telum.ru

Denis Fakhriev
Telum
23 Trubnaya str.
Moscow, Russia 127051
fakhriev@telum.ru

ABSTRACT

This paper presents a novel approach to a low-resolution modeling of wireless networks in ns-3. This model relies on automatic neighbor estimation based on current channel conditions. This estimation constructs a basis for automatic collision avoidance among interference neighbors at MAC layer and for a global topology construction using communication neighbors of each station. There are several verification examples that show an ability of a spatial reuse of the allocated bandwidth. A case study example shows the intended use of this model.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design - Wireless Communication

Keywords

ns-3, network simulation, MANET

1. INTRODUCTION AND MOTIVATION

Wireless networking is one of the most popular application areas for network simulators today. Approximately 45% of ns-3 codebase is somehow related to wireless communications.

In the ns-3.12 model library one can find several popular wireless standards: IEEE 802.11 (Wi-Fi), IEEE 802.16 (WiMax), 3GPP LTE and up to an exotic Underwater Acoustic Networks (UAN). A model of IEEE 802.15 is currently being developed. Among the routing protocol models one can find a number of MANET ones: OLSR, AODV, DSDV and PacketBB for future NHDP and OLSRv2. DSR model is under the code review. There is a flexible framework for broadband radio communication modeling (“spectrum” module [1]) as well as a number of radio propagation loss models (“propagation” module). Of course, modeling mobility of the network nodes was not overlooked (“mobility” module). Most of these models are continuously updated.

Like all models in general [2], wireless communication models are based on some simplifying assumptions about modeled technology. In theory model developers and users are free to select a level of abstraction needed for *their particular* simulations. Practically, however, models are reused many times and model developers try to satisfy all users including as many details about modeled system as they can do in the packet-level simulator. Models of this sort are usually referred to as high-accuracy models and tend to be implementations of the relevant standards in the ns-3 environment. The champion in this directions is probably the detailed Wi-Fi PHY model [3] developed in Karlsruhe Institute of Technology.

At the same time there is a strong motivation for the simpler wireless models with less level of details about physical and link layers. We will refer to these models as *low resolution* ones in this paper to contrast with *high resolution* detailed models. Here are the reasons:

First, network simulation can be used at the very early stages of system development, e.g. during requirements analysis. At this stage few details about physical and link layers of a future system are known. Popular solution is to use some “appropriate” available model, frequently the Wi-Fi one, to prototype a new device in the simulator. Using this approach is particularly hard to distinguish between Wi-Fi artifacts and universal wireless communications effects such as interference and packet loss.

Second, the details of the physical and link layers can be unknown or unavailable. Many real-world devices, especially in the public safety and military domains, use proprietary radio modems for wireless communications. Modeling these equipment researcher typically knows only some basic information from the commercial data-sheets: frequency range, bandwidth, channel speed, TX power and RX sensitivity. No details about PHY and MAC algorithms and protocols are usually given.

Third, protocol developers frequently tend to compare the performance of their solutions with the “optimal” ones. Low resolution models based on a number of simplifying and “idealizing” assumptions can play a role of the reference points in the performance analysis of real protocols and systems.

Fourth, there is always a resolution/complexity trade-off. Low complexity of low resolution models potentially allows the user to overview the whole system and *understand* its behaviour. Since low resolution allows to document explicitly all assumptions, low resolution models can be easily verified and extended when needed. Finally, obviously enough low resolution models are supposed to run faster and require less

WNS3 2012, March 23, Desenzano del Garda, Italy

DOI 10.4108/icst.simutools.2012.247700

memory which can be important for the large scale simulations.

With this motivation in mind we have developed the Low Resolution Radio (LRR) model for ns-3. Model source code is freely available, see [4].

The rest of the paper is organized as follows. Next section provides a brief overview of the related work. Section 3 summarizes all model assumptions. The LRR model consists of the radio channel model plus the modular physical (PHY), channel (MAC) and ad-hoc routing layers, described in section 4. Section 5 illustrates the intended use of the model and gives some ideas about its validity for specific use cases. Section 6 concludes the paper.

2. RELATED WORK

The idea to keep a global object, that tracks the status of the network is not new in the simulation world. NS-2 [5] has a GOD (General Operations Director) object, which keeps a global state of the network including a shortest paths table. It is stated that GOD is used by MAC models, but its main purpose is a network monitoring, which gives an estimation of a routing protocol efficiency and provides a topology representation. Network topology is precomputed from nodes positions and then loaded from the mobility traces before the simulation run. Topology knowledge obtained in the same manner has driven us to create an "idealized" routing protocol which is simple to implement and does not require any management traffic exchange (see section 4.4 for details). In contrast to GOD our routing model updates topology using current wireless channel conditions and updates it continuously during simulation run.

The idea of a simple time division multiple access model for wireless networks is not also new for ns-3. There is a Simple Wireless TDMA [6] model which is under the code review. Multiple access is organized by continuous repetition of a pre-defined slot map. This slot map describes a fixed-duration medium access grants for every node and can not be changed during the simulation run, which limits the ability of the spatial reuse in mobile scenario. Another problem may be concerned with a manual slot allocation: the slot map is loaded from the file. This method may limit the usage of this model in scenarios with big and multi-hop networks, because user must estimate spatial-reuse ability before constructing a slot map. In contrast, slots are allocated on-demand in our model, which gives a scalable and automatic collision avoidance and provides a spatial reuse.

Junseok Kim has developed a simple CSMA/CA model for ns-3 [7]. The model is a simplified (in comparison with Wi-Fi model in ns-3) model of CSMA/CA protocols with RTS/CTS mechanisms implemented and based on the NS-2 802.11 model. The model was developed to give users an easy ability to enhance model's functionality and test some new features and algorithms. This example shows, that users are interested in simple, easy-to-understand models in order to conduct their own research. Unfortunately, this model is not technology-independent and only Wi-Fi features may be investigated.

In addition to routing and medium access mechanisms, there is a physical layer, which plays a very significant role in the network, because the most of the model assumptions are concentrated at this layer of the network stack [8]. On the other hand, MANET studies require answering the questions concerned with the multi-path and frequency-selective propagation environment, the inter-channel interference [9] between devices of different technologies operating in a common wireless channel or the impact of the industrial noise. All these factors belong to the channel and PHY layers too. As soon as our model should be scalable, it has to reflect all aspects of big and complex networks and it has to be still simple. Spectrum-aware physical layer modeling framework [1] provides a flexible solution which fulfills such requirements. Its run-time and complexity depends mostly on the signal representation complexity. One may find a balance between run-time and accuracy using the same set of models and changing only a signal representation. Our model is based on this framework.

3. MODEL ASSUMPTIONS

This section presents a list of all assumptions made in the LRR model. Assumptions are numbered and divided into separate groups, each of which belongs to one of four levels of the protocol stack: C – Channel, P – Physical layer, M – Medium access, R – routing.

(C-1) Channel gain is assumed to be a function of the transmitter and receiver positions, frequency and time only.

(C-2) Channel gain is assumed to be frequency independent ("flat") in the system's spectrum band.

(C-3) All devices use the same isotropic antennas with a known gain which is a model parameter.

(P-1) Noise at the receiver is assumed to be a thermal noise, defined by its Boltzmann spectral density, plus a noise figure which is a model parameter.

(P-2) At any given moment of time the physical layer is assumed to be in one of three possible states: transmission (TX), reception (RX) when the device is synchronized to the received signal and idle (IDLE).

(P-3) PHY changes its state from IDLE to RX only at the beginning of a packet reception. Switching to RX happens only if the instant received signal power exceeds a threshold *EDThresholdDbm*. ED stands for energy detection which is a model parameter. Note, that signal has to pass through the receiving filter before the comparison with *EDThresholdDbm*.

(P-4) When the transceiver changes its state to RX, its synchronization is assumed to be preserved until the end of a packet receiving time (capture effect on the physical level is not modeled).

(P-5) It is assumed that all devices use identical modulation and coding scheme with a known bitrate which is a model parameter

(P-6) It is assumed that all devices use the same constant transmission power which is a model parameter.

(P-7) Packet is assumed to be successfully received if and only if during the whole reception time SINR was greater than a threshold *MinSinrDb*, which is a model parameter.

(P-8) Nodes are assumed to have one or more radio devices, operating at distinct frequency channels.

(M-1) Time division multiple access (TDMA) method is assumed.

(M-2) MAC level control traffic is not modeled.

(M-3) MAC is assumed to completely avoid collisions occurring in the network.

(M-4) ARQ is not modeled.

(M-5) Link layer segmentation and reassembly is not modeled.

(M-6) Link layer header has a known fixed size which is a

model parameter.
(M-7) 48-bit link layer addresses are assumed.
(M-8) The minimum time interval between consecutive transmitted packets *GuardInterval* is assumed, which is a model parameter. This models a propagation delay guard, duration of the preamble and the average channel access delay.
(M-9) No link layer QoS policy is modeled.
(R-1) The routing protocol is assumed to be a proactive and a link-state one.
(R-2) The routing protocol is assumed to be based on IPv4.
(R-3) The routing protocol control traffic is not modeled.
(R-4) The hop count routing metric is assumed.
(R-5) It is assumed that all nodes at every moment have the same representation of the network topology.
(R-6) The routing protocol is assumed to support both a unicast and a multicast destinations.

4. MODEL DESCRIPTION

The LRR model is a network device with modular PHY (sect. 4.2) and MAC (sect. 4.3). To communicate all LRR devices should be connected to the same wireless channel (sect. 4.1). Global MANET routing protocol model (sect. 4.4) can be installed on the IP layer to provide multihop connectivity. Note, however, that any other routing protocol can be used on top of LRR device, an example is given in section 5.

4.1 Channel

The LRR radio channel model is based on the SpectrumChannel model of the spectrum framework, see [1]. Its main task is to calculate the attenuation of the transmitted radio signal between the sending and receiving devices.

The model assumes explicit separation of signal attenuation in the channel into two components:

$$G_{ch} = G_D + G_S\,, \tag{1}$$

where

- deterministic pass loss G_D depends on the center frequency and the relative position of the transmitting and receiving nodes;
- stochastic attenuation G_S models shadowing and fast fading and is a function of nodes' position and time.

It is assumed that time average of the G_S is zero, therefore time average channel gain equals its deterministic component only. This allows one to find all communication neighbors of every device (see the next section).

4.2 PHY

The LRR physical layer model is based on the HalfDuplexIdealPhy model from the spectrum framework (see [10] with the following distinctive functions).

First, LRR PHY can determine a list of the LRR devices within the time average communication range – *CommunicationNeighbors*. To do this PHY model periodically estimates the time average (e.g. deterministic component only) channel gain to all other LRR devices and selects ones with acceptable estimated receiving signal strength. Transmission power, minimum reception SINR (see assumption P-7), thermal noise and noise figure (see assumption P-1) are taken into account. The device is listed as communication neighbor if

$$\mathit{RxPowerDbm} - \mathit{RxNoiseDbm} \geq \mathit{MinSinrDb} + \mathit{LQMarginDb} \tag{2}$$

where

$$\mathit{RxPowerDbm} = \mathit{TxPowerDbm} + 2G_{antenna} + G_{ch} \tag{3}$$

and

$$\mathit{RxNoiseDbm} = 10\log_{10}(kT\Delta f) + \mathit{NF}\,. \tag{4}$$

The only non-trivial term above is a $\mathit{LQMarginDb}$ where LQ stands for link quality and which is a constant shift, which accounts for the stochastic channel gain component and removes too weak links from the analysis. Communication neighbors lists are used to build a global network topology to be used by the routing model as described below.

Second, LRR PHY can determine a list of LRR devices which can interfere with it when transmitting simultaneously – *InterferenceNeighbors*. The procedure is two step. First, one-hop interference neighbors are defined as (see assumption P-3):

$$\mathit{RxPowerDbm} \geq \mathit{EDThresholdDbm} - \mathit{LQMarginDb} \tag{5}$$

where $\mathit{RxPowerDbm}$ is defined above. Second, all one- and two-hop interference neighbors (neighbors of neighbors except given device itself) are assumed to be in the PHY's *InterferenceNeighbors* list. Note that the same value of $\mathit{LQMarginDb}$ which is used in (2) to shrink the communication neighborhood is used in (5) to extend interference neighborhood and account for stochastic channel gain component.

4.3 MAC

The LRR medium access control (MAC) model schedules packet transmissions in a coordinated way to avoid simultaneous transmissions of the interference neighbors (see definitions in the previous section). Every LRR MAC instance i at every given moment of time can schedule a single transmission. The scheduled transmission is described by two timestamps: $\mathit{TxStart}(i)$ and $\mathit{TxEnd}(i)$ for the transmission start and end respectively. Packets wait for their transmissions in the MAC queue.

LRR MAC schedules a new transmission when the packet arrives to the empty queue or when the transmission of the previous packet is completed and the queue is not empty. The scheduled transmission start time is coordinated with all interference neighbors:

$$\mathit{TxStart}(u) = \max_{v}\ \mathit{TxEnd}(v) + \mathit{GuardInterval}\,, \tag{6}$$

where $v \in \mathit{InterferenceNeighbors}(u)$ and $\mathit{GuardInterval}$ are model parameters (see assumption M-8).

The transmission end timestamp is then derived depending on the packet size (including fixed MAC layer header length, see assumption M-6) and PHY bitrate (see assumption P-5):

$$\mathit{TxEnd}(u) = \mathit{TxStart}(u) + \mathit{size}/\mathit{bitrate} \tag{7}$$

The described scheduling algorithm allows for spatial spectrum reuse and avoids collisions as long as the interference neighbors list is properly defined by the PHY model (see previous section).

In the LRR implementation PHY model computes interference neighbors on demand and MAC model is responsible to limit the computational load and does not recalculate interference neighbors more often than once per *InterferenceNbrUpdatePeriod* time interval.

4.4 Routing

The LRR device and channel described in the previous three sections can be used with any network layer protocols. At the same time communication neighbors provided by the LRR PHY model can be used to create a global network topology graph and global MANET routing model on top of it. This is implemented in the LRR routing model. This model can be viewed as a generalized model of any proactive link-state MANET routing, OLSR being the well known example. In contrast to many real routing protocols our model supports the multicast operation as well as the unicast one.

The LRR routing model periodically updates communication neighbors lists of all LRR PHYs and combines them into single network topology matrix. When a change is detected in the topology, unicast routing tables for all LRR nodes are updated using a well known Floyd-Warshall all-to-all shortest paths algorithm.

Collision free scheduling provided by the LRR MAC model allows us to create simple and efficient multicast forwarding and routing scheme. IP packets with multicast destination address are forwarded with broadcast MAC layer address by the relay nodes, selected to do so by the LRR routing model. To select relays for given multicast group M and source IP address src LRR routing model "glues" all unicast routes from src to all $dst \in M$ to the multicast routing tree. All vertexes of the tree are then selected to be multicast relays from src to M. The single multicast routing table, i.e. a set of relays for every known multicast group M and every $src \in M$ is updated every time when unicast routing tables are updated.

The list of all known multicast groups $\{M\}$ and a map from the multicast IP address to the list of unicast IP addresses of the group members $M \rightarrow \{src\}$ is managed by the singleton object which is accessed from the simulation script. The singleton can be viewed as a simplest model of the group management protocol.

Additional care is taken to make the unicast and multicast LRR routing model work correctly with nodes with multiple LRR interfaces. No routing to the non-LRR IP interfaces is provided. This routing scheme may be achieved by the existing ns-3 methods.

4.5 Model Parameters

All LRR model parameters and their default values are listed in table 1. Note, that default values do not necessarily make sense for your particular use case.

4.6 Verification

A set of unit tests ships with the model which check the ability of the node to transmit and receive packets over the LRR wireless channel and ability of the routing protocol to deliver packets to the unicast and multicast destinations without any loss or duplicates.

There are several simulation examples which calculate an achievable throughput between nodes in some simple topologies. Such examples help to ensure that the medium access protocol uses allocated bandwidth efficiently and avoids collisions. To check the absence of collisions one may use FlowMonitor module. As soon as there is no ARQ at the MAC layer, 100% packet delivery is the evidence of collision-free medium access. Results of these examples are demonstrated below.

Parameter	Default value
$EDThresholdDbm$	-99 dBm
T	300 K
Δf	20 MHz
NF	0 dB
$LQMarginDb$	0 dB
$bitrate$	6 Mb/s
$TxPowerDbm$	16 dBm
$G_{antenna}$	0 dBi
$MinSinrDb$	8.6 dB
$MacHeaderSize$	14 bytes
$GuardInterval$	100 μs
$MSDU$	1500 bytes
$InterferenceNbrUpdatePeriod$	0.5 s
$TopologyUpdatePeriod$	1 s

Table 1: Model parameters

First example checks a TCP throughput between two stations. We have chosen 6 Mbit/s PHY bitrate and created a network with default parameters (see table 1). The average value of the throughput equals 4.6 Mbit/s, which corresponds to the default TCP segment length and $GuardInterval$ value in the LRR MAC. As a reference, we have conducted the same experiment with Wi-Fi model where the average throughput was about 3.9 Mbit/s.

The second example experiment is conducted in the chain topology. We have measured a TCP-throughput between the first and the last nodes. As soon as MAC model allows spatial reuse, chain topology is the best test case demonstrating this. Each node of this chain may communicate only with the nearest neighbor. Interference neighbors list of each node contains two nodes from each side of the chain (4 nodes total). To include some random background traffic we have used OLSR routing protocol on top of LRR devices.

The results of this experiment are presented in table 2, where the dependency of the throughput (Thr.) in Mbit/s vs. the chain length in hops is presented. The measure responsible for the spatial reuse is a multiply of chain length and throughput Length×Thr, because all data sent by the source is repeated by each node during forwarding to the destination.

Length (hops)	2	3	4	5	6	7
Thr. (Mbit/s)	2.11	1.46	1.26	1.14	1.05	1.00
Length×Thr.	4.22	4.38	5.04	5.70	6.27	7.00

Table 2: Chain throughput

5. CASE STUDY: VIDEO OVER MANET

In this section we illustrate an intended use of the LRR model. For this demonstration we choose a scenario with a MANET network deployed in the area of a rescue operation. Detailed model of nodes' movements in such scenario is presented in [11]. We used the scenario example provided in that work without any changes except the number of nodes. Table 3 presents the number of nodes associated with each rescue area.

Area	Nodes	Transport units
Incident location	15	15
Patients waiting for treatment area	15	10
Casualties clearing stations	20	0
Ambulance parking point	5	5
Technical operational command	5	0

Table 3: Mobility scenario parameters

Portable video cameras are mounted on a helmet of each rescuer working in the accident area. Every camera sends a continuous video stream to the technical operational command. In accordance with table 3 there are 15 continuous unidirectional video streams in the network.

Single video stream has a pixel size images 177×144 and refresh rate of 20 frames per second, its coding is carried out using the MPEG-4 codec. The average bit rate of the stream is about 80-100 Kbit/s. We have obtained the statistics of distribution of the video-frame lengths of the video stream, as well as frame-length correlation properties by processing real video records using the procedure proposed in Section 18.5 of [8]. An autoregressive model was used to generate a random process responsible for reference frames. Other frames are generated independently from each other. The code of video stream application as well as the described here scenario are available as a part of the model examples.

Since most of the work on assessing the performance of MANET networks use the model of IEEE 802.11 and very popular OLSR, we provide a comparison of the network performance depending on the medium access and routing mechanisms. We have tested two medium access solutions (IEEE 802.11 and LRR) and two routing solutions (LRR and OLSR). Note, that we can not make a simulation of IEEE 802.11 and the LRR routing model together since 802.11 model does not support communication neighbors computation. Simulation setup parameters are listed in table 4. Parameters with default values are not listed.

Parameter	Value
Propagation environment	
Loss exponent	3
Fast Fading	no
Communication range	≈ 90m
LRR PHY settings	
Noise source	Thermal only, 290 K
Bandwidth	20 MHz spectrum
RX-filter	Ideal, no-loss
Data rate	6 MB/s
Tx-power	16 dBm
LRR MAC settings	
GuardInterval	114 μs
OLSR settings	
TC Interval	1.25 s
HELLO Interval	0.5 s
REFRESH Interval	0.2 s
802.11 MAC settings	
Coding and modulation scheme	OFDM 20 MHz 6 Mbit/s
Simulation setup settings	
Simulation Time	900s
App start time	50 + Uniform (0,1) s
Number of runs	20
ns-3 version	3.12.1

Table 4: Simulation setup

During the simulation we have tracked some properties of the network topology, constructed by OLSR and LRR routing protocols. The network diameter is 3-4 hops for all runs and the number of links as seen by routing protocols is about 950-1050. The average number of node's communication neighbors is ≈ 20. The path length of video-streams is 2 or 3 hops depending on mobility conditions. The network is multi-hop one and each node has a possibility to communicate with any other node in the network during the whole simulation time. Note, that this properties of the constructed network are independent from protocols chosen.

Simulation results are presented in table 5 in the form of the average delay and packet delivery ratio for all possible combinations of protocols. The first row of this table illustrates the LRR performance.

One may conclude that the data rate of 6 Mbit/s is sufficient to deliver all the data to be transmitted in this scenario. One may also notice that the OLSR also solves this task but the network load has increased due to additional OLSR management traffic. Hence, the average delay has also increased from 7 up to 70 ms. It should be noted that the choice of routing protocol configuration may dramatically change the network performance. Thus, using default OLSR parameters, only 63% PDR may be achieved. This is caused by frequent route damage due to very high mobility (relative to the communication range). We have observed the maximum node's velocity about 11 m/s while the communication range is only about 90 m. If correctly configured, OLSR has an equal possibility of successful data delivery in comparison with the global LRR routing protocol and provide almost the same PDR values.

Routing	MAC	Avg. PDR	Avg. Delay
LRR	LRR	97.9%	7.7 ms
OLSR	LRR	97.3%	72.0 ms
OLSR	Wi-Fi	64.8%	209 ms

Table 5: Simulation results

The random access mechanism of IEEE 802.11 is unable to deliver packets to the destination over a multi-hop path. High overhead caused by backoff procedure and retries due to collisions in a dense network lead to inefficient usage of the allocated bandwidth. In addition, there is a high loss rate of OLSR management packets. Different stations relying on the obsolete data have different or even wrong topology representation. This shows obvious advantage of the collision free deterministic time division access over the random access mechanisms like IEEE 802.11. The poor efficiency of the IEEE 802.11 is caused by high node density: there are about 20 stations inside a communication range. If each station tries to access the medium, collisions are almost guaranteed: CW has a uniform distribution between 0 and 15 during the first transmission attempt.

Routing	MAC	Time	Memory
LRR	LRR	348 s	6.4 M
OLSR	LRR	3314 s	23 M
OLSR	Wi-Fi	1572 s	23 M

Table 6: Run-time and memory consumption

The run-time of a single simulation run and the memory consumption as the function of the used models is presented in table 6. It is worth to notice significant difference between OLSR and the LRR routing run-time performance. There is almost a tenfold difference (first and second rows of the table). This is caused by very time-consuming MPR and shortest paths computations triggered by each reception of OLSR packet on every node regardless of actual topology changes. In contrast, the LRR model does not compute MPR sets and tracks actual topology changes before it initiates shortest paths computations. The second reason why the LRR model is faster than the OLSR model is that the LRR has a global topology database rather than per-node topology computations. This fact allows us to assume higher run-time difference in case of larger networks. Memory consumption is also an important factor. Imagine a big network with the same node density as in our scenario. Suppose also, that topology is kept in a form of a list of all communication links. If the density of nodes is constant, the amount of required memory has linear dependence on the network size, because the average number of communication links for each node is approximately constant. This leads to the fact that a simulation with 600 nodes may require 2.2 GB of memory in case of the OLSR and only 640 MB in case of the LRR routing model. 2.2 GB of memory makes impossible to execute several simulation runs in-parallel. Note, that the OLSR traffic may be modeled at the application layer and the LRR routing may be used for route computation.

An interesting fact is that the IEEE 802.11 model executes faster than the LRR MAC model(third and second rows of the table 6 respectively). This is caused by OLSR management traffic loss, and, as a consequence, the most time-consuming MPR and shortest paths computations become less frequent.

6. CONCLUSIONS AND OUTLOOK

We have designed and implemented a novel low resolution radio model for ns-3. This model relies on automated communication and interference neighbor detection at channel and PHY layer, collision avoidance among interference neighbors at MAC layer and routing model with a global topology derived from communication neighbors of each station. This model is simple and easy-to-understand: the amount of source code of the whole stack is much less than, say, in the ns-3 802.11 model.

The LRR model is verified and has a number of simulation examples. Verification of the model has shown, that MAC layer is able to use the allocated bandwidth efficiently with a spatial reuse ability. The model ships with a case study example and a video-stream application model. The case study example has shown the differences in performance of different medium access and routing protocols.

We see two main ways to continue this work. First, LRR model can be used in various specific wireless simulation cases to understand its application and validity area. Second, the model can be extended in the different ways:

- modeling link layer and cross layer QoS policies;
- ARQ and HARQ modeling;
- modeling routing metrics;
- modeling link adaptation: dynamic rate and power control

just to name a few.

7. REFERENCES

[1] Nicola Baldo and Marco Miozzo. Spectrum-aware channel and PHY layer modeling for ns3. *Proceedings of the Fourth International ICST Conference on Performance Evaluation Methodologies and Tools*, page 2, 2009.

[2] George E.P. Box in Wikiquote. `http://en.wikiquote.org/wiki/George_E._P._Box`.

[3] PhySimWiFi for NS3. `http://dsn.tm.uni-karlsruhe.de/english/ns3-physim.php`.

[4] Code review issue: Low Resolution Radio Model for ns-3. `http://codereview.appspot.com/5466046`.

[5] The Network Simulator NS-2. `http://isi.edu/nsnam/ns/`.

[6] Simple Wirelss TDMA. `http://codereview.appspot.com/4747046/`.

[7] Simple CSMA/CA Protocol for NS3. `http://www2.engr.arizona.edu/~junseok/simple_wireless.html`.

[8] Klaus Wehrle, James Gross, and Mesut GÃijnes. *Modeling and Tools for Network Simulation*. Springer-Verlag Berlin Heidelberg, Berlin, Heidelberg, 2010.

[9] Mario Gerla. From battlefields to urban grids: New research challenges in ad hoc wireless networks. *Pervasive Mob. Comput.*, 1:77–93, March 2005.

[10] Half-Duplex Ideal PHY model. `https://www.nsnam.org/docs/release/3.12/doxygen/group__spectrum.html`.

[11] Nils Aschenbruck, Elmar Gerhards-Padilla, Michael Gerharz, Matthias Frank, and Peter Martini. Modelling mobility in disaster area scenarios. In *Proceedings of the 10th ACM Symposium on Modeling, analysis, and simulation of wireless and mobile systems*, MSWiM '07, pages 4–12, New York, NY, USA, 2007. ACM.