A Wireless Mesh Network NS-3 Simulation Model: Implementation and Performance Comparison With a Real Test-Bed

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Abstract—**Wireless mesh networks present an attractive communication solution for various research and industrial projects. However, in many cases, the appropriate preliminary calculations which allow predicting the network behavior have to be made before the actual deployment. For such purposes, network simulation environments emulating the real network operation are often used. Within this paper, a behavior comparison of real wireless mesh network (based on 802.11s amendment) and the simulated one has been performed. The main objective of this work is to measure performance parameters of a real 802.11s wireless mesh network (average UDP throughput and average one-way delay) and compare the derived results with characteristics of a simulated wireless mesh network created with the NS-3 network simulation tool. Then, the results from both networks are compared and the corresponding conclusion is made. The corresponding results were derived from simulation model and real-world test-bed, showing that the behavior of both networks is similar. It confirms that the NS-3 simulation model is accurate and can be used in further research studies.**

Keywords: **wireless mesh networks, 802.11s, HWMP, network simulation, NS-3.**

I. INTRODUCTION

A concept of wireless mesh networks (WMN) has become popular among academic researchers and telecommunication industry within the last decade. The most attractive property of such networks is a possibility of rapid and cost-effective deployment of networks with ability to provide high-capacity services for an end-user. Moreover, a diversity of wireless mesh networks applications is very wide, making it a convenient solution to use them in various projects in diverse areas, such as transport (VANET) [1], civil and military communication infrastructures, environment and public safety [2][3].

At Anhalt University of Applied Sciences (HSA), the Future Internet Lab Anhalt (FILA) is currently conducting a couple of projects with extensive usage of wireless mesh technologies. During the implementation stage of these projects, a question of adequate performance evaluation of WMN arises. As a solution of this problem, a networking simulation environment NS-3 is proposed to be used [4]. Based on the simulation, it is possible to imitate, run and to see a network behavior with any topology, size, mobility, wireless medium parameters and traffic profiles and intensity. To do that, we need to implement a simulation environment, which behavior will be adequate and comparable to a behavior of a real wireless mesh network under real conditions. This is the main objective of this paper.

For a real-world test-bed, a 802.11s wireless mesh networking standard [5] has been used – an open80211s Linux implementation [6], in particular. For the simulation model – an NS-3 networking simulator with implemented 802.11s MAC-layer stack [7] is chosen. As for performance parameters – an average UDP throughput and an average delay will be evaluated in both test-bed and simulation model.

A. Test-bed description

To be able to compare parameters of the simulated network with a real-world scenario, a test-bed network has been deployed. The network consists of 4 wireless nodes placed in 2x2 grid topology with a distance between them equals to 1 meter. The topology of the test network is illustrated on Fig.1.

As the network's node, an ARM-based system-on-chip (SoC) had been used with a wireless 802.11 adapter based on rt2800 mesh-compatible driver [8]. Then, a Linux OS with modified kernel and the open80211s [6] implementation of the mesh standard has been installed on the SoC [9] (as in Fig. 2).

A mesh mode was switched on with HWMP routing protocol with default Airtime Link routing metric [10], equation (1):

$$c_a = \left[O + \frac{B_t}{r} \right] \cdot \frac{1}{1 - e_f},\qquad(1)$$

where

c_a – the airtime cost;

O – a constant, which defines a channel access time depending on the used physical implementation (802.11a, 802.11b);

B_t – test packet size (8192 bits);

r – channel data rate (Mbps);

e_f – packet error probability.

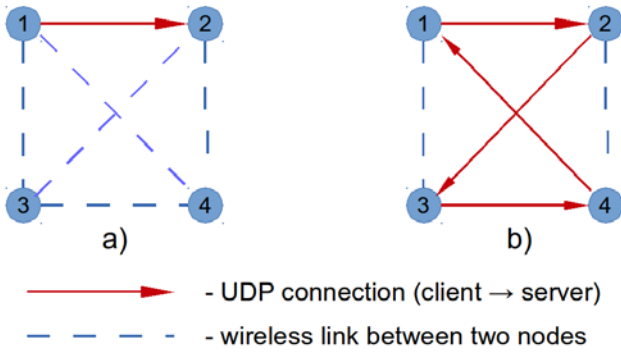Fig. 2. The open80211s stack integrated into the Linux kernel.

Fig. 1. Test network topology with two experiments:
a – 1 UDP connection;
b – 4 simultaneous UDP connections.

To evaluate r and e_f values, a node sends a block of test packets. The length of the test packet is a default value which is set by the standard – 8192 bits.

In a case of independent packet errors, the packet error probability can be calculated as (2):

$$e_f = 1 - (1 - p_o)^n \approx np_o, \qquad (2)$$

where
p_0 – transmission bit error probability;
n – number of bits being transmitted.

B. Simulation description

For the simulation purposes, NS-3 network simulator has been used [4] [11]. NS-3 is a discrete-event simulator with a special focus on Internet-based systems, consisting of different library components (core, simulation, node libraries, physical and channel models, network routing protocols implementations, etc.) written in C++. Such structure allows researchers to modify, adjust and simulate various networking scenarios. The general simulation architecture of NS-3 [11] is depicted on Fig. 3.

In order to simulate the real-world test-bed as accurate as possible, a few main network characteristics must match:
–   the same 2x2 grid static topology;
–   propagation loss model;
–   physical interference model;
–   modulation scheme and the frequency range (802.11g, 6Mbps OFDM rate);
–   802.11s peer-link management protocol and HWMP parameters;

The 802.11g modulation standard has been used in both simulation and real test-bed since this is the most recent specification which is supported by the current 802.11s
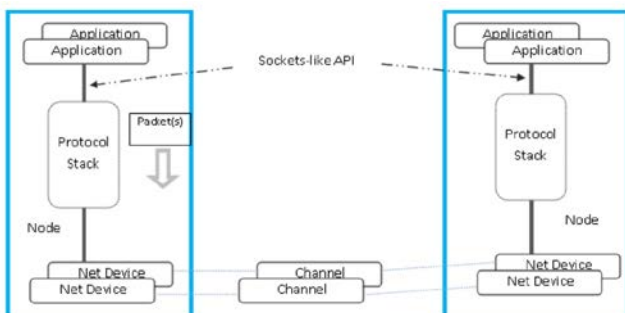

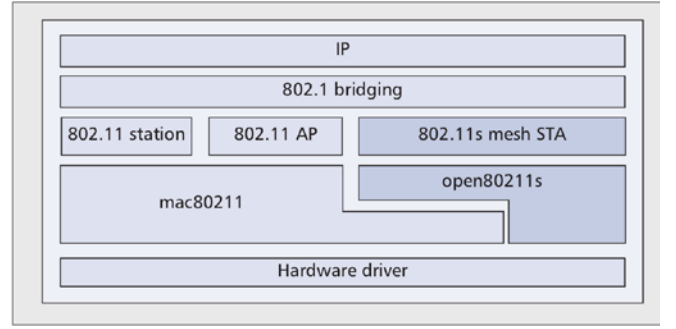Fig. 3. NS-3 main simulation objects.

implementation (open80211s). The 802.11n standard is not supported yet by mesh devices.

HWMP stands for Hybrid Wireless Mesh Protocol, which is used as a default multi-hop routing scheme in 802.11s standard.

One of the important parameters used in the simulation is the chosen propagation loss model which should consider the real-world wireless medium irregularities such that various obstacles (walls, doors, people, etc.) and interferences (electrical equipment, other wireless systems, etc.). These factors decrease the signal strength in different ways.

In NS-3, there are several available propagation loss models [11]: fixed RSS loss model, Friis propagation loss model, Jakes propagation loss model, Nakagami propagation loss model, random propagation loss and log distance propagation loss models. They are used in different wired and wireless communication scenarios.

For our case, where the distance between the nodes is short and static, and the measurements are conducted in a building, the Log-Distance Propagation Loss Model [11] was the most suitable and adaptive. This model calculates the reception power (received signal strength) using the following equation (3):

$$L = L_0 + 10 \cdot n \cdot \log_{10}\left(\frac{d}{d_0}\right), \qquad (3)$$

where
L_0 – path power loss (signal attenuation) at reference distance (dB);
n – the pass loss distance exponent;
d – distance (m);
d_0 – reference distance (m);
L – path power loss (signal attenuation) (dB).

To adapt this propagation loss model to a real test-bed, correct values of these variables has to be found. A YansWifi [11] physical interference model has been used to simulate the signal's interference; a frequency range and modulation scheme have been taken from 802.11g standard with 6 Mbps bitrate. 802.11s HWMP routing parameters have been set to default values.

II.   THE 802.11S ROUTING SCHEME

A 802.11s standard was developed by IEEE 802.11 task group in 2006 with main objective to overcome the limitations of traditional Wi-Fi star topologies (Access Point – Clients) and to enable a deployment of wireless mesh
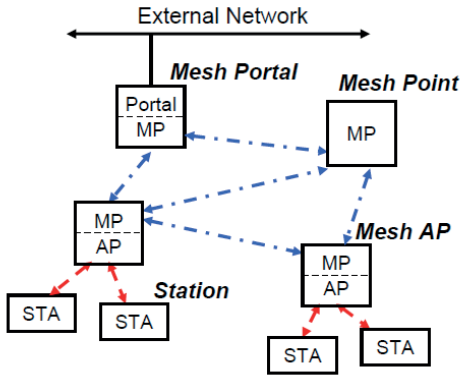
Fig. 4. A general architecture of 802.11s WMN network.

networks based on 802.11 MAC layer with layer-2 (L2) multi-hop routing scheme, provided by HWMP.

A general 802.11s based WMN architecture is shown in Fig. 4. It consists of 4 classes of devices [9]:
- Mesh Point (MP) – wireless mesh node with data routing and forwarding functionality;
- Mesh Access Point (MAP) – wireless mesh node with additional functionality of wireless access point (AP), allowing different wireless clients to connect to WMN;
- Mesh Portal (MPP) – a gateway connecting WMN with another external networks;
- Stations (STA) – wireless 802.11 devices connected to MAP;

Currently, the 802.11s standard categorizes frames as data, control and management frames. Control frames are used for exchanging acknowledgements and path reservation messages, whereas the management frames perform a function of establishing and maintaining the WMN. The 802.11s frame format provides additional mesh control fields for data routing over multiple hops, including source address (initial hop), destination address (final hop) and mesh source address [10].

III. HWMP PROTOCOL

Hybrid Wireless Mesh Network Protocol belongs to the class of so-called hybrid routing schemes, which means that it can work in both proactive and active modes alternatively or simultaneously.

In the reactive mode (Fig. 5a), the node's forwarding table is created right before the beginning of data transmission. Upon sending the data packets, a source node sends a broadcast Path Request (PREQ) message to its neighbors which change the Air-Time Metric value and forward it further. A sink node receives the PREQ and sends back a Path Reply (PREP) message back to the source. When the source node gets the reply (PREP), it obtains the information about the whole path (path metric) and makes a transmission decision [12].

In the proactive mode (as in Fig. 5b), the wireless mesh network has to set a root node, which transmits broadcast root requests (RREQ) in order to form a path tree. In such case, every mesh node has the information about how to deliver data packets to every other node through the root beforehand.
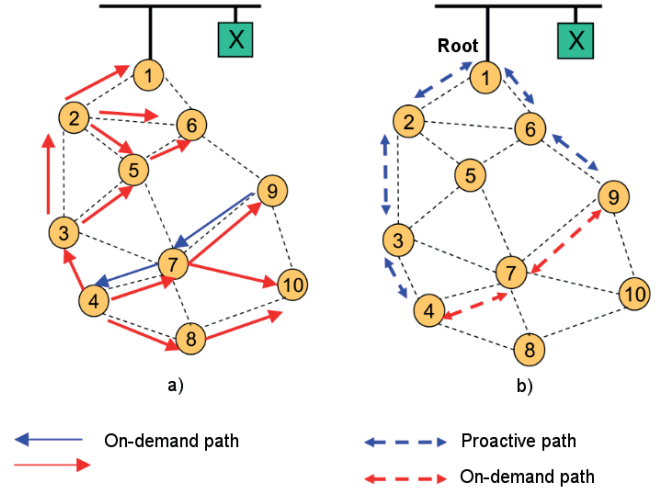

Fig. 5. Connection establishing between nodes 4 and 9: [5]
a – in HWMP reactive mode;
b – in HWMP proactive mode.

IV. EXPERIMENT MAP

As it has been mentioned above, the test topology of the WMN (real-world test-bed and NS-3 simulation script) represent a 2x2 grid with 1 m distance between two nodes, as it is illustrated on Fig.1.

Two main performance parameters are chosen for the evaluation – average UDP throughput and average one-way delay. A network traffic load parameter (in the form of a number of simultaneous UDP connections) is chosen as a variable value.

In the real-world test-bed, the throughput value of the generated UDP traffic is estimated by the client side of the iperf utility [13] after the channel having been loaded according to its established transmission bitrate.

The average one-way delay (OWD) under different traffic loads was measured using LTest tool [14]. The LTest utility generates UDP traffic with fixed data rate and calculates one-way delay from that. However, in contrary to measurements of RTT, on OWD, a high-precision time synchronization of the corresponding CPU clocks is crucial, which is provided by LTest. This provides highly accurate one-way delay values between sender (client) and receiver (server).

The duration of each test in the real-world test-bed as well as in the simulated network has been set to 100 seconds. The UDP packet size and each client's UDP stream data rate have been set to 1024 Bytes and 6 Mbps correspondingly.

In the simulation script, the aforementioned parameters were calculated using formulas (4) and (5):

$$R_{avg} = \frac{N_{rec.bits}}{T_{lastbit} - T_{firstbit}}, \qquad (4)$$

where

$N_{rec.\ bits}$ – number of received bits;

$T_{last\ bit}$ and $T_{first\ bit}$ – time of the last and the first bits received correspondingly;

$$OWD_{avg} = \frac{T_{TOTAL}}{N_{rec.packets}}, \qquad (5)$$

where

T_{TOTAL} – total transmission time;

$N_{rec.\ packets}$ – number of received packets.

V. MEASUREMENT AND SIMULATION RESULTS

After having conducted a number of experiments, we derived the dependencies of average throughput and average one-way delay as functions of UDP traffic load (number of UDP connections each with 6 Mbps data rate). It was stated that as the traffic load increases, a common wireless mesh network decreases significantly due to physical characteristics of wireless transmission medium (noisy environment, increasing interference) and current open80211s implementation. This fact is confirmed by the NS-3 simulation, where a similar behavior is detected. In general, the simulated average throughput values correspond to the ones from the test-bed (as in Fig. 6). The absolute average throughput values in the worst case differ in about 34%, and in the best case – 14%.

Furthermore, the average one-way delay increases as the number of UDP connections grow in both real test-bed and simulated networks with a very similar behavior. It can be explained with the fact that the 802.11s standard is mostly based on 802.11 MAC-layer which exploits CSMA/CA multiple access scheme. Therefore, with the increasing network traffic, the number of frame retransmission quickly increases, affecting the overall delay. Moreover, the current 802.11s implementation (open80211s) is still under extensive development and sometimes we were faced with unstable network behavior under very high loads. However, under medium traffic loads, the real-world test-bed network behavior is stable, which is confirmed by the simulation illustrated on Fig. 7.

The average throughput values derived from both scenarios and their percentage difference are presented in Table 1. As it can be seen from the numbers, the relative difference between the real test-bed and the simulation model does not exceed 35% in the worst case (2 UDP connections), and is equal approximately to 14% in the best case (3 UDP connections). The simulation model becomes more accurate when there are two and more simultaneous connections, which can be explained by the fact that the signal interference starts to play the most significant role in the network performance behavior, and the YansWifi signal interference model is well-implemented in NS-3 simulator.

In Table 2, the average one-way delay values and their corresponding percentage difference are presented. In this scenario, the similarity in the real test-bed and the simulation model behaviors is even better. The worst percentage difference is only 24% and the best one is 14%. In this case, it is quite difficult to establish the relation between UDP traffic intensity and the simulation model accuracy. These random fluctuations in accuracy deviations can be explained only by the randomness of wireless channel model used in NS-3 simulator and by unpredictable behavior of the real wireless medium.
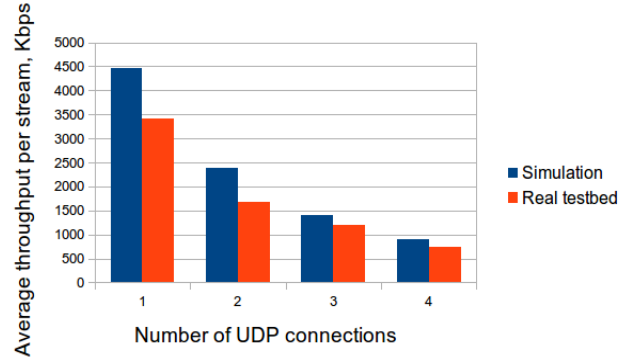

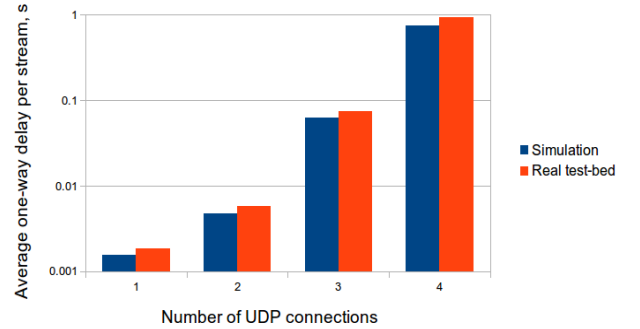Fig. 6. Average UDP throughput per stream behavior in real test-bed and simulation.

Fig. 7. Average one-way delay per stream in real test-bed and simulation.

TABLE I
AVERAGE THROUGHPUT VALUES OF REAL TEST-BED AND SIMULATION, (KBPS)

Number of UDP connections	1	2	3	4
Simulation, Kbps	4471.6	2387.8	1403.6	908.3
Real test-bed, Kbps	3415.8	1677.3	1209.3	744.7
Percentage difference	26 %	34 %	14 %	19 %

TABLE II
AVERAGE ONE-WAY DELAY VALUES OF REAL TEST-BED AND SIMULATION, (MS)

Number of UDP connections	1	2	3	4
Simulation, ms	1.54	4.81	62.85	743.1
Real test-bed, ms	1.84	5.84	73.86	946.34
Percentage difference	17 %	19 %	16 %	24 %

All in all, a discrepancy in the calculated values is acceptable and can be explained by non-ideal wireless physical medium (additional noise sources, random noise, etc.), occasional unstable behavior of open80211s implementation and wireless driver (rt2800) as well as current 802.11s model characteristics in NS-3. However, the similarity between test-bed and simulated network model is clearly seen.

VI. CONCLUSION

Basing on the results derived from the experiments, we can observe that the behaviors of the real test-bed and the simulated network are quite similar. It means, that the physical, interference and channel models in NS-3 simulator are set with sufficient accuracy and fit to the purposes of evaluation performance parameters of different wireless mesh networks with various topologies. Moreover, the

802.11s protocol stack (Peer Link Management protocol and HWMP) implemented in NS-3 adequately imitates hybrid routing schemes and link establishing algorithms of real wireless mesh network implementation based on open80211s.

Therefore, the experiment results allow us to conclude that the proposed NS-3 simulation model can be used for wireless mesh networks performance evaluation with satisfactory accuracy in ongoing FILA projects (SoCiEr, Smartlight) as well as in any future projects which involve wireless mesh networking communication.

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