LICENTIATE THESIS

Network State Estimation in Wireless Multi-Hop Networks

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To my family.

ABSTRACT

Multi-hop wireless networks in general and those built upon IEEE 802.11 standard in particular are known for their highly dynamic and unstable performance. The commonly accepted way for improving the situation is to jointly optimize the performance of protocols across different communications layers. Being able to characterize a state of the network is essential to enable the cross-layer optimization. This licentiate thesis investigates methods for passive characterization of network state at medium access control and transport layers based on information accessible from the corresponding layers below.

Firstly, the thesis investigates a possibility for characterizing traffic intensity relying solely on the statistics of measurements from the physical layer. An advantage of this method is that it does not require decoding of the captured packets, by this accounting for the effect from long-range interferences introduced by transmissions at the border of the communication range of a receiver.

Secondly, a question of predicting TCP throughput over a multi-hop wireless path is addressed. The proposed predictor is a practically usable function of statistically significant parameters at transport, medium access control and physical communication layers. The presented model is able to predict the TCP throughput with 99% accuracy, which provides an essential input for various cross-layer optimization processes.

Finally, during the course of the experimental work the issues of accuracy of simulation-based modeling of communication processes were investigated. The thesis is concluded by presenting a comparative study of the performance characteristics measured in a single channel multi-hop wireless network test-bed and the corresponding measurements obtained from popular network simulators ns-2 and ns-3 when configured with identical settings. The thesis presents the evaluation of the mismatch between the results obtained in the test-bed and the simulators with their standard empirical radio models.

CONTENTS

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Anna Chaltseva
Luleå December 2011

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CHAPTER 1

Thesis Introduction

Multi-hop ad-hoc wireless networks and specifically those built upon IEEE 802.11-based technology received significant attention in research community during the last decade [1]. Such networks are a promising technology to provide the Internet access due to the possibility of rapid and low-cost deployment. In an ad-hoc network each node operates as a host and a router at the same time. Hence if the destination node is not within the transmission range of the source node, one or more intermediate nodes along a path would assist in forwarding packets.

However, several drawbacks prevent the wide deployment and popularization of multi-hop ad-hoc networks. The IEEE 802.11 medium access control (MAC) protocol is known for its inefficient performance due to intrinsic random media access mechanism together with the specific characteristics of wireless medium [2, 3, 4]. It was also shown that the performance of the TCP protocol over multi-hop wireless paths is far from being acceptable for most of traditional applications [5, 6, 7, 8, 9, 10, 11].

Enormous research efforts on understanding the reasons for the unstable performance of multi-hop wireless networks and its improvements have been invested during the last ten years. It was shown that the traditional layered design of the communication stack is not efficient for multi-hop wireless networks [12, 13]. In wireless networks the functionalities of communication layers become highly interconnected. For example, a decision at the MAC layer regarding allocating a particular channel determines the available bandwidth, which in turn affects the congestion control mechanism of the TCP protocol and vice versa [13]. Therefore in order to optimize the performance of a multi-hop network, one needs to jointly optimize the functionality across the layers [1, 14]. This licentiate thesis investigates methods for passive characterization of network state at medium access control and transport layers based on information accessible from the corresponding layers below. This information then can be used for various optimization processes.

Firstly, the thesis investigates a possibility for characterizing traffic intensity relying solely on the statistics of measurements from the physical layer. An advantage of this method is that it does not require decoding of the captured packets, by this accounting for the effect from long-range interferences introduced by transmissions at the border of the communication range of a receiver.

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Finally, during the course of the experimental work the issues of accuracy of simulation-based modeling of communication processes were investigated. The thesis is concluded by presenting a comparative study of the performance characteristics measured in a single channel multi-hop wireless network test-bed and the corresponding measurements obtained from popular network simulators ns-2 and ns-3 when configured with identical settings. The thesis presents the evaluation of the mismatch between the results obtained in the test-bed and the simulators with their standard empirical radio models.

This introductory chapter is structured as follows. The introduction to the problem area is in Section 1.1. The research questions are formulated in Sections 1.2. Section 1.3 overviews the results presented in details in the included articles. Sections 1.4 summarizes the thesis and presents a set of open questions for future work.

1.1 Introduction to the problem area

Section 1.1 presents the introduction to the problem area describing problems with MAC-layer performance and issues related to its optimization in multi-hop wireless networks, issues related to TCP throughput estimation, and challenges associated with accurate simulations.

1.1.1 Problems with MAC-layer performance and issues related to its optimization in multi-hop wireless networks

Radio interference is the main performance limiting factor in wireless networks. One source of interference is other stations transmitting in geographic proximity of the node question and sharing the same communication channel. Additionally, the interference can be caused by external sources of electromagnetic waves such as microwaves, other networks operating on an overlapping channel, etc [15].

At the MAC layer interferences manifest themselves in a so called "extended hidden terminal" problem [3, 16, 17]. Consider a chain of wireless nodes forming a multi-hop network in Figure 1.1. The transmission range of each node covers its direct neighbors. The transmission range of a wireless node is the maximum distance on which a wireless signal can be correctly received and decoded by other nodes. The interference range is the area beyond the transmission range where the transmitted signal is not strong enough to deliver decodable data, however, it is strong enough to disturb the reception of data from other nodes. The interference range is typically twice wider than the transmission range. As shown in the figure node 4 interferes with the data communication ongoing between nodes 1 and 2. More precisely, node 4 continues sending packets to node 5, while node 1 keeps on retransmitting the corrupted packet

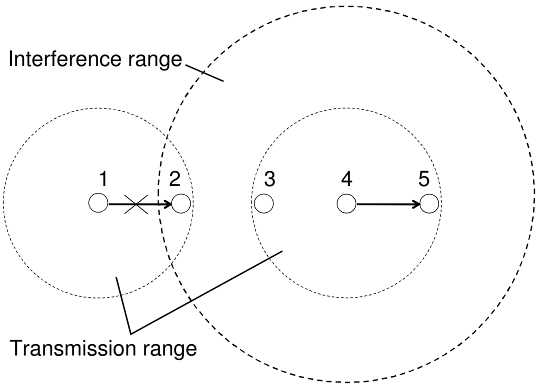

Figure 1.1: The extended hidden-terminal problem

to node 2 until it drops the packet when reaching the retry limit. Therefore, nodes 1 and 4 are hidden with respect to each other.

Several techniques have been developed for mitigating the effect of interferences. Among the most effective ones are smart antennas with power control at the physical layer [18] and contention resolution type of techniques at the MAC layer [19, 20, 21].

Smart antennas

Smart antennas possess a signal-processing capability to optimize their receive or transmit characteristics automatically according to the current state of the channel [22, 23]. The smart antennas are classified as multiple-input single-output (MISO), single-input multiple-output (SIMO), and multiple-input multiple-output (MIMO). Depending on the optimization criteria, multiple received signals can be combined to improve the quality of the reception or can be processed separately into multiple data streams to increase bandwidth.

Contention resolution type of techniques at the MAC layer

Contention resolution type of techniques at the MAC layer adapt the transmission parameters (channel/frequency, transmission rate, transmission power, etc.) depending on the current state of the communication channel. The channel state includes for example interference level, aggregated traffic load, spacial nodes distribution. The optimization techniques based on contention resolution require the knowledge of characteristics of the aggregated traffic, which includes spatial distribution of data flows [24], density of active users [25, 26, 27], queue occupancies [28, 29]. Several techniques were proposed to estimate the number of active neighbors [26, 27]. Using Kalman filter technique, the collision probability could be related to the number of actively transmitting nodes in theory [25].

In [28, 29] a contention resolution scheme based on the estimated occupancy of the queues in individual nodes is presented. These and other related methods require successful recep-

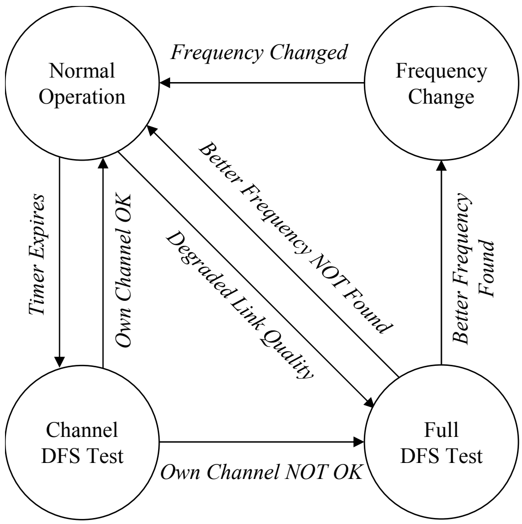

Figure 1.2: Finite state machine for a DFS algorithm

tion of data packets for their operation. As such the effect of long range interferences is not captured.

Another class of schemes for MAC performance optimization bases their work on the estimation of the channel utilization [30, 31, 32]. The “h” extension of the IEEE 802.11 standard [30] defines a *Dynamic Frequency Selection* (DFS) mechanism. The main idea of DFS is to reduce the interferences between wireless nodes. It is done by performing three types of measurements on a channel: basic, CCA (Clear Channel Assessment), and RSSRI (Received Signal Strength Report Indication) measurement [33]. By the first type of measurements a node detects an existence of other stations communicating on the same channel. The CCA measurement allows to estimate the period of time the channel was occupied by other communications. RSSRI measurement corresponds to the monitoring of a media, recording periods when the signal corresponds to a certain RSSI value, and the following quantization. Figure 1.2 illustrates the state diagram for the DFS algorithm with four states: Normal Operation, Channel DFS Test, Full DFS Test, and Frequency Change [34].

1.1.2 TCP throughput estimation

Initially, TCP was developed to operate over wired networks where it is assumed that all packet losses occur because of buffer overflow in routers due to network congestion. However, this basic assumption is not true for wireless connections because of such channel properties as a high bit error rate (BER) and variable bandwidth. Each time the TCP sender detects a loss of a segment by means of the retransmission timer (RTO) expiration, it retransmits the lost

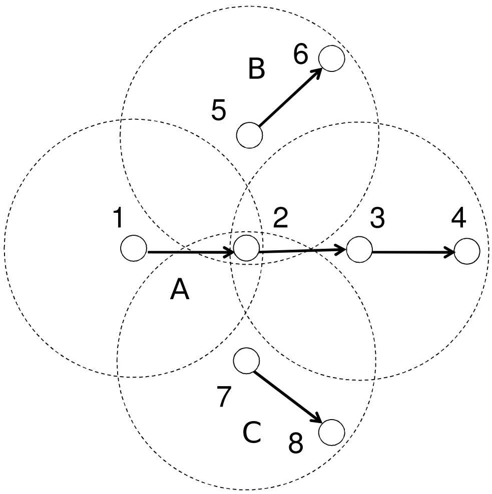

Figure 1.3: Flow in the middle problem

segment, doubles RTO, reduces the TCP congestion control window threshold and the current size of the congestion window.

In the wireless multi-hop network all nodes share the same medium in a certain area. When one node performs congestion control, this influences all other nodes within the area. Several problems with TCP performance were discovered over the last ten years. One of the problems is related to a so called "flow in the middle" scenario. In this scenario the performance of the TCP affected flow can be degraded due to the activities of other flows. As illustrated in Figure 1.3 flows A, B, and C share the available bandwidth. Node 2 experiences more interference from nodes 1, 3, 5 and 6 than other nodes. Hence, the source node 1 will reduce its rate by shrinking its congestion window. This would reduce the interference at nodes 5 and 7. As the result, they will become less congested and increase their rates. This in turn would lead to a situation when the interference around node 2 would intensify and the TCP source at node 1 would further reduce its rate. Therefore flow A would become congested at node 2.

One way to mitigate the problem is described in [35], where the authors propose a network layer rate control mechanism in order to reinforce fairness. This mechanism relies on the knowledge of ideal TCP throughput and the number of competing flows obtained from the routing protocol. Several approaches to model TCP throughput over multi-hop wireless network exist [36, 37, 38, 39]. One of the most common predictors which is largely used in the Internet is the "square root" model [40]. This model defines the average TCP throughput as a function of the the Round-Trip Time (RTT) and the loss rate [41].

$$E[R] = \frac{M}{T \cdot \sqrt{\frac{2 \cdot b \cdot p}{3}}} \tag{1.1}$$

In (1.1) $E[R]$ is the expected TCP throughput, M is the maximum TCP segment size, and b is the number of TCP segments released per ACK, while T and p are the RTT and average loss rate respectively. The inaccuracy of this model reveals in the case when packet losses are recovered by the fast-retransmission mechanism. The improved "square root" formula (or PFTK predictor) as presented in [42] takes into account retransmission timeouts and a limited maximum window size:

$$E[R] = min(\frac{M}{T \cdot \sqrt{\frac{2 \cdot b \cdot p}{3}} + T_0 \cdot min(1, \sqrt{\frac{2 \cdot b \cdot p}{8}} \cdot p \cdot (1 + 32 \cdot p^2)}, \frac{W}{T}) \quad (1.2)$$

where T_0 is the TCP retransmission timeout period and W is the maximum TCP window size.

However, it was shown that the PFTK predictor can result in large prediction errors [41]. Another problem is that the PFTK predictor as well as the traditional "square root" formula require knowledge of the network parameters which are unknown in advance, such as round trip time and loss rate.

A good overview and an extensive analysis of the available TCP throughput prediction approaches is presented in [36]. These approaches can be divided into two groups: the ones, which are using analytical methods, such as [43, 44, 45, 46], and others, which are applying empirical manner, real-measurements and simulations [38, 39]. The main drawbacks of the analytically derived solutions are their complexity for practical usage in applications, model limitations and simplified assumptions [37]. An empirical approach to determine TCP flow behavior over multi-hop wireless networks is presented in [38]. As the result, the authors recommend some TCP and IEEE 802.11 parameters that are best for TCP performance over multi-hop wireless networks. However, it was shown by different methods [47, 48] that these values can vary with different scenarios.

1.1.3 Simulation tools

The time-varying characteristics of the wireless medium and the complex interdependences between communication layers make it hard to consistently obtain the general understanding of processes inside wireless networks. This understanding can come from an analytical analysis, the examination of data measured in a real test-bed, and investigations based on simulations. The major part of the work presented in this thesis is simulation-based. Since it is hard to orchestrate repeatable experiments by using real equipment, the question of accuracy of the used network simulators is, therefore, of ultimate importance for the validity of the findings presented in the thesis.

A large number of research publications were devoted to the accuracy of simulations [49, 50, 51]. The authors in [52] presented a comparative study between an IEEE 802.11a based test-bed and three network simulators (ns-2, QualNet and OPNET). As a result, the simulation outcomes match to some extent with the test-bed. The authors highlight that tuning of physical layer parameters and selected propagation models have a great impact on the results.

In [53] the authors presented a validation study of the IEEE 802.11b MAC model in ns-3 by comparing simulations with test-bed results. The study demonstrated that the results from ns-3 simulations nearly match with the reality after proper tuning of the devices in the test-bed. It was also shown that in the case of mismatching between the simulation and test-bed results, it is not always a problem with the simulator. Specific selection and configuration of the devices in the test-bed can be culprit.

The authors in [54] pointed out the disparities between a wireless network test-bed, ns-2, and Qualnet. The disparities were explored based on antenna diversity, path loss, multi-hop, transmission rate, interference and routing stability. However, ns-3 simulations had not been taken into account and intra-path interference was discussed only for a single flow traffic over a linear multi-hop network.

Experimental validations of simulations results were also done in [55]. The goal of this work was to validate a wireless network model built with ns-2 by comparing the network characteristics of a simulated, an emulated, and a real wireless network. This comparative study was done with respect to three network performance metrics: network connectivity graph, packet delivery ratio, and latency. The authors demonstrated that these characteristics are represented in the wireless model with an acceptable average error.

1.2 Research questions

More formally, this licentiate thesis answers the following research questions:

1. *Is it possible to derive a PHY-layer characterization of the aggregated traffic on a wireless link by a statistical analysis of time series of the received signal strength?*
2. *How to construct a predictor of TCP throughput using information from network, MAC and physical layers?*
3. *How well do commonly used simulators reflect the reality with their standard empirical radio modeling capabilities?*

1.3 Overview of results

This section provides an overview of the results described in details in the articles included in the second part of the thesis.

1.3.1 Paper A

On passive characterization of aggregated traffic in wireless networks

In this thesis the results on the passive characterization of the aggregated traffic on micro- and millisecond's time scale using time series of the signal strength measured at the physical layer are presented. Figure 1.4 illustrates the approach taken in this work. The recorded time series of the signal strength are used to model the traffic arrival process during (discrete) time interval $[t-n, t]$. The model's outcome is used to predict an aggregated *traffic intensity* during

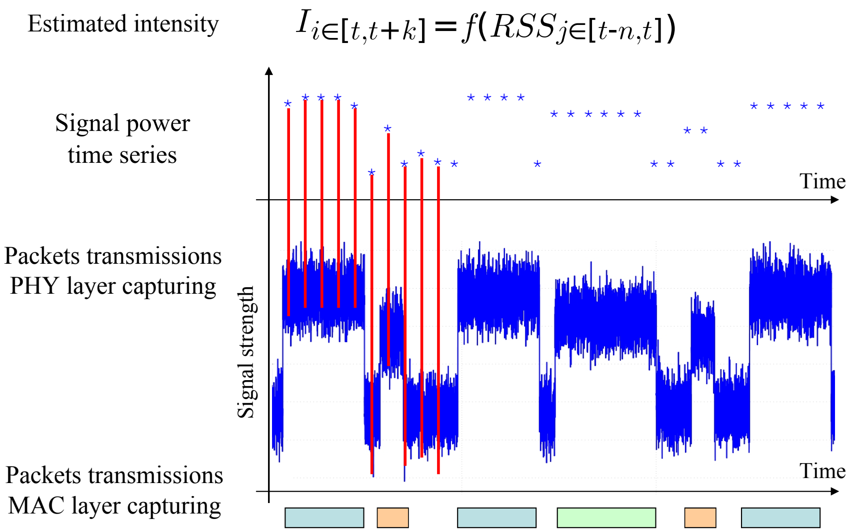

Figure 1.4: Approach taken to answer the first research question.

time interval $[t, t+k]$ needed to send a pending for transmission data packet at the MAC layer. If the approach is successful, the traffic intensity predicted in this way could be used to adjust the parameters of the MAC layer (e.g. size of contention window, retransmission strategy, etc.), in order to minimize the packet collision probability.

Research methodology

The approach taken to answer the first research question follows from the rich experience collected in the wired networks research community on characterization and modeling of the aggregated IP traffic. Traffic characterization by observing the packet arrival process and the packet size distribution has been well explored in wired networks [56, 57, 58]. The major difference between analyzing an aggregated traffic on a wired bottleneck link and doing so on a wireless link is in the broadcast nature of the later. At a wireless receiver packets transmitted by nodes in the same radio range may not be correctly decoded due to bit errors caused by interferences. Therefore, our methodology to answer the second research question consists of three phases: data gathering; randomness and correlation analysis; and modeling and assessment.

Data gathering: All data for further analysis and modeling were obtained in a controllable manner in a radio isolated chamber. We experimented with traffic of different intensities and used a spectrum analyzer to accurately record the signal strength time series with microsecond's sampling time.

Randomness and correlation analysis: In this phase we firstly examined a statistical dependence in the recorded time series. In other words, whether it is possible to use the physical layer's statistics for characterization of the aggregated traffic intensity or not. The results of the

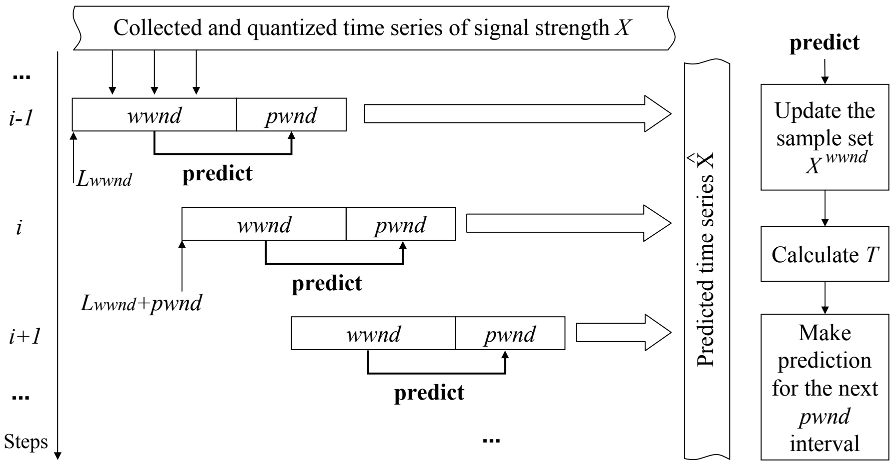

Figure 1.5: The model algorithm.

two-sample Kolmogorov-Smirnov test allowed us to proceed with the analysis of nature of the statistical dependence by studying the correlation structure of the series described in the same section.

Modeling and assessment: Finally, we built a two-state Markov model of the channel occupancy and used it to predict the traffic intensity during a time interval chosen with reference to the transmission time of data structures of different length (e.g. short control frames and maximum size of a data packet). The rationale for doing this step is simple, if we are able to correctly predict the channel occupancy on packet transmission time scale, we may use this result further to optimize the transmissions of the pending packets.

Results

Paper A presents a practical measurement-based model of the aggregated traffic intensity on microsecond's time scale for wireless networks. In order to check the hypothesis that the recorded time series of the signal strength have a statistical dependency, the two-sample Kolmogorov-Smirnov test [59] was performed. The outcome of the test allows the rejection of the null hypothesis with 1% significance level. We also show that the recorded signal strength time series have short-range dependent correlation structure.

Our approach towards modeling is illustrated in Figure 1.5. A two-state Markov model is constructed using data collected during time interval called *working window*. The constructed model is then used to predict the presence or absence of the signal during the immediately following time interval called *prediction window* (*pwnd*). The size of the prediction window is chosen with reference to the time needed to transmit a data structure of certain length with a given transmission rate at the physical layer.

We choose two values of $pwnd$ in order to illustrate our reasoning: one equals the time it takes to transmit the shortest data structure (RTS frame) with the rate 1Mb/s: $pwnd = 200$

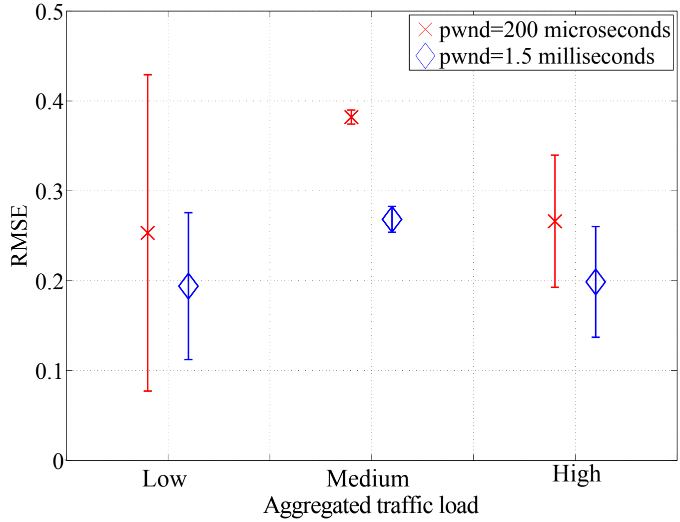

Figure 1.6: The proposed model accuracy.

microseconds. The other value equals the time it takes to transmit the maximum size packet (1460 Bytes) with the highest transmission rate 11Mb/s in our case: $pwnd = 1.5$ milliseconds. The rationale for choosing these values stems from the goal of this work - we want to optimize the performance of the MAC protocol prior to a pending packet transmissions.

Figure 1.6 illustrates the accuracy of the derived model for different aggregated traffic loads and different values of $pwnd$. We observe that the accuracy of the model is substantially lower for the short $pwnd$. Although for some parts of traces with low traffic intensity the model introduced 10% error, the average error for all traffic loads ranges between 0.25 and 0.4. On the other hand for the larger $pwnd$ the average value never exceeds 0.3 for all traffic loads. In particular in the case of high traffic load our models shows 0.2 prediction error.

My contribution

I performed all technical and analytical work reported in this article. This includes setting up and conducting the experiments in the isolated chamber as well as performing analysis and modeling. The text of the article was jointly written with my supervisor.

1.3.2 Paper B

Empirical Predictor of TCP Throughput on a Multi-hop Wireless Path

A question of predicting TCP throughput over a multi-hop wireless path is addressed in Paper B. Analytical derivation of the throughput predictor for multi-hop wireless networks is difficult if not impossible at all due to complex cross-layer dependencies. In this paper we statistically analyze the significance of parameters at physical, MAC and transport layers in a multi-hop wireless chain and empirically derive a practically usable throughput predictor. The resulting model allows the prediction of the throughput with less than 2% error.

Research methodology

To answer the second research question, we propose a *two-stages* methodology for empirical derivation of the TCP throughput predictor. The goal of the *first stage* is to determine the optimal subset of parameters statistically significant for optimization. In order to archive that, we perform a factorial design and use the F-test to evaluate the significance of the chosen parameters. At the *second stage* we accomplish iterative curve fitting on the parameters with the highest statistical significance. On each iteration the parameter with the highest significance is chosen, curve fitting is performed and the accuracy of fitting is evaluated by using a coefficient of multiple determination. The procedure is repeated for all significant parameters. To collect the necessary statistics for the first and second stages of our approach, the ns-2 simulations were conducted with prior careful calibration of the network simulator parameters.

Results

Paper B presents the approach for empirical derivation of the TCP throughput predictor on a multi-hop wireless path. The main idea of this approach is to obtain the TCP throughput model in *a general* form (1.3), where R_{PHY} is the gross data rate at the physical layer and $f(\overrightarrow{P_{ENV}}, \overrightarrow{P_{MAC}}, \overrightarrow{P_{NET}}, \overrightarrow{P_{TRAN}})$ is the rate reduction coefficient. This coefficient is a function of parameters at the physical, MAC, network, transport layers and $\overrightarrow{P_{ENV}}$ is a vector of characteristics of particular operating environment.

$$\hat{R} = R_{PHY} \cdot f(\overrightarrow{P_{ENV}}, \overrightarrow{P_{MAC}}, \overrightarrow{P_{NET}}, \overrightarrow{P_{TRAN}}). \tag{1.3}$$

As it was mentioned previously, a two-stages methodology was used to derive the target model. In the first stage, the statistical analysis of the experimental data led to identify the following parameters as significant: number of wireless hops (nh) and the maximum size of TCP segment (MSS) with confidence 95%. However, the minimum contention window size at MAC layer and the maximum congestion window of TCP were significant only in some small part of the experiments. Therefore, these parameters were excluded from the following model construction. This statistical analysis was further expanded in section 4.1 of this paper where linear regression was introduced as a way to perform an iterative throughput modeling based on three selected parameters: nh, MSS, and R_{PHY}.

As a result of iterative fitting a three-dimensional variant of the model (1.4) was obtained, where $\overrightarrow{\alpha}$, $\overrightarrow{\beta}$ and $\overrightarrow{\gamma}$ are vectors of scalar values for each considered physical layer transmission rate.

$$\hat{R}(R_{PHY}, N_{hops}, MSS) = R_{PHY} \cdot \frac{MSS + \overrightarrow{\alpha}}{\overrightarrow{\beta} \cdot N_{hops} - \overrightarrow{\gamma}}. \tag{1.4}$$

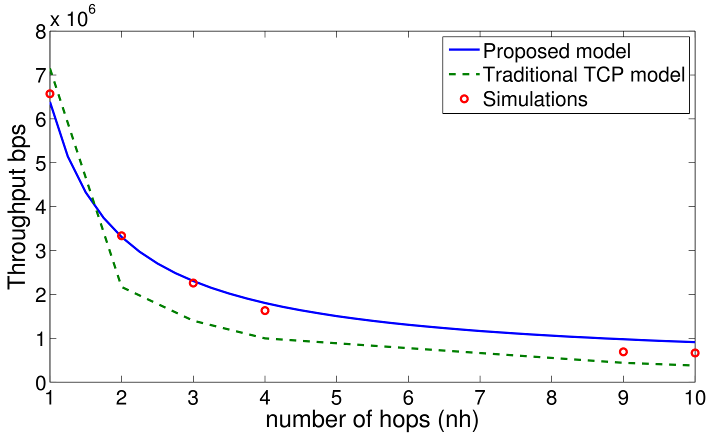

Figure 1.7: TCP throughput measured in simulations, predicted by the final model and PFTK predicor for R_{PHY}=54Mb/s and MSS=1460B versus number of hops.

The coefficients in vectors $\overrightarrow{\alpha}$, $\overrightarrow{\beta}$ and $\overrightarrow{\gamma}$ can further be expressed as functions of other parameters. Determining these parameters was left outside the scope for this paper. The proposed model allows practical prediction of TCP throughput with less than 2% error (Figure 1.7).

My contribution

I performed all technical work including the design of the experiments and performing all simulations. All statistical analysis and modeling work is also my contribution. The text of the article was written jointly with my supervisor.

1.3.3 Paper C

Comparison of Wireless Network Simulators with Multi-hop Wireless Network Test-bed in Corridor Environment

Paper C presents a comparative study between results of a single channel multi-hop wireless network testbed and the network simulators ns-2 and ns-3. It was explored how well these simulators reflect reality with their standard empirical radio modeling capabilities. The environment studied is a corridor causing wave-guiding propagation phenomena of radio waves, which challenges the radio models used in the simulators.

Research methodology

The methodology applied in this work consists of two stages: experimental and analytical. The experimental stage includes the real test-bed measurements and the simulations. The IEEE802.11b based multi-hop wireless test-bed was placed in an indoor corridor environment in a non-linear chain topology. Such arrangement challenges the commonly used empirical models of wireless propagation channel that are currently available in ns-2 and ns-3. The experiments done for this study included single and concurrent flows transmissions over a single multi-hop path. The test-bed experiments were replicated in network simulators ns-2 and ns-3. The second stage of this work was based on the measurements collected during the experimental stage. We performed the comparative analysis of the results from test-bed, ns-2, and ns-3 with the following conclusion.

Results

Paper C presents a comparative study between multi-hop wireless test-bed and the network simulators ns-2 and ns-3. The test-bed was located in the university corridors and consisted of eight nodes placed in a non-linear chain topology. The experiments were performed with single and concurrent flows transmissions over a single multi-hop path. While reproducing the test-bed experiments by using ns-2 and ns-3, we paid special attention to the proper configuration of the wireless channel properties: the path loss and multi-path fading models. In the indoor environment, the propagation of radio waves is mainly affected by two types of losses: the path loss and the loss due to small and large scale fading. The small scale fading arises due to the multi-path propagation effect and the large scale fading is due to the shadowing effect. Therefore, the simulations were based on usage of log-distance path loss and Nakagami fading models. In order to find a better match of the path loss and multi-path fading with the real test-bed, the simulations were conducted for five combinations of the path loss exponent (n) and five Nakagami fading parameters (m).

The simulation results from both ns-2 and ns-3 showed that none of the fading parameters m has a persistent match with the test-bed results in all multi-hop scenarios. We also observed that in contrast to ns-3, the ns-2 simulations have a closer match with the test-bed results except for six and seven hops cases, where ns-2 results are diverging from the test-bed larger than ns-3. Therefore, it is hard to conclude which of the two simulators closer reflects the reality except for stating that both simulators give a rough match of the test-bed results.

The comparative study of the results for the scenario with concurrent traffic transmissions was done with respect to throughput fairness index. Figures 1.8 and 1.9 suggest that fairness index behaviours of both simulators are quite different from the test-bed, which implies that average throughputs behaviours of simultaneous flows of simulations are also different from the test-bed. As we observed from Figures 1.8 and 1.9 the fairness indexes obtained from the ns-2 and ns-3 simulators have opposite trends for different values of simultaneous flows and the number of hops.

Overall, as in the "single-flow" case, none of the simulators was able to exactly reproduce the performance of the test-bed. The major problem in our opinion comes from the inability of the simulator's propagation models to capture all signal impairments mechanisms in the particular communication environment. The corridor environment of the test-bed exposes strong wave-guiding propagation phenomena, which places a great impact on the accumulative interference and the spatial reuse ratio.

However, simulations deviate more clearly from the test-bed results for simultaneous flows transmissions. These transmissions increase the accumulative interference compared to single

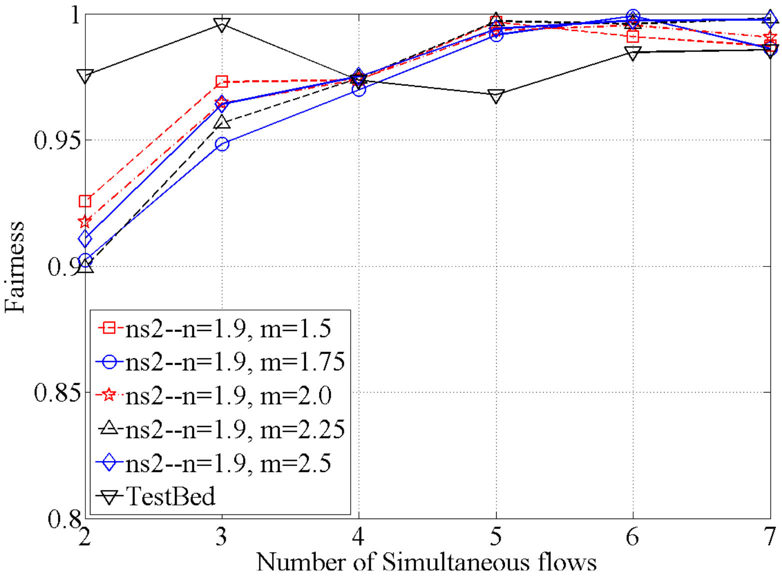

Figure 1.8: Jain fairness index for simultaneous flows transmissions versus ns-2 results for path loss exponent $n = 1.9$ *and different Nakagami parameters* m*.*

flow transmissions and thereby decreases the spatial reuse ratio of the network. In particular, for simultaneous flows transmissions, simulations indicate considerably worse fairness between flows compared to test-bed results. This reveals that the wireless propagation channel models of the simulators are not correctly representing the wireless channel properties in the corridors, especially in scenarios involving accumulated interference in difficult environments such as corridors. Obviously, there is no model with 100% accuracy and it is expected that the simulations results may deviate from the reality. Therefore, it is important to understand the degree of reality reflected by the simulators. The contribution of our article can be formulated as “there is a strong need in validation of such models before using them to simulate single channel multi-hop wireless networks”. We have showed the unreliability of results generated by ns-2 and ns-3 in the scenarios with single and concurrent flows transmissions over a single multi-hop path.

My contribution

This work was performed together with two my colleagues PhD students. During the work I equally contributed to the design of the experiments, building the test-bed and conducting the tests. I conducted all simulations in ns-2 and equally participated in the analysis of the results. I also contributed to writing of the article’s text.

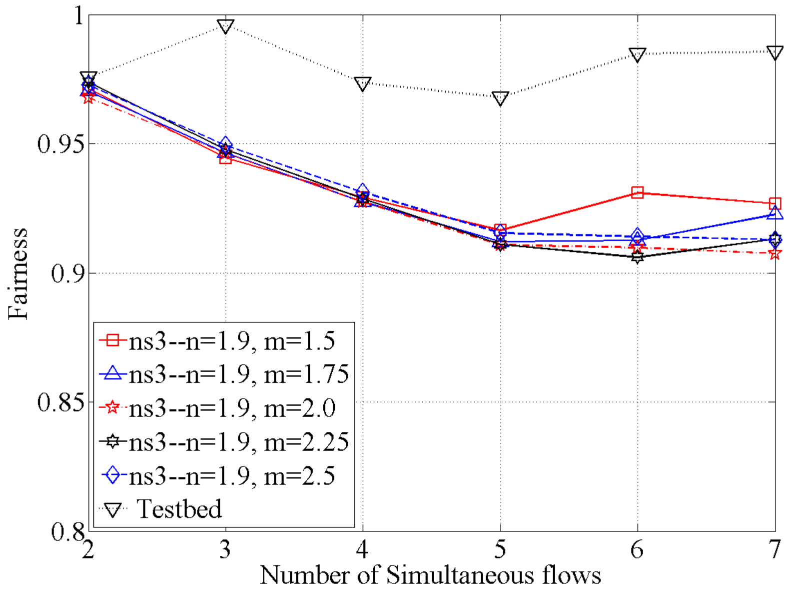

Figure 1.9: Jain fairness index for simultaneous flows transmissions versus ns-3 results for path loss exponent $n = 1.9$ and different Nakagami parameters m.

1.4 Summary

In summary we present answers on the research questions and state the directions for future work.

1. *Is it possible to derive a PHY-layer characterization of the aggregated traffic on a wireless link by a statistical analysis of time series of the received signal strength?*

   On the positive side we show that the statistics collected at the physical layer do not behave randomly and it is valid to use this information for characterization of the aggregated traffic in the vicinity of a wireless transmitter. While showing the feasibility of the micro-scale traffic characterization we conclude that more efforts should be spend to increase the accuracy of the prediction as well as developing mechanisms for using this information to improve the performance of next generation cognitive MAC protocols.

   The resulting model opens a possibility to mitigate the effect of interferences in the network by optimizing the parameters of the MAC layer for the forthcoming transmission based on the predicted aggregated traffic intensity based on short-term historical data. The presented model is based on the collected statistics in the wireless test-bed network located inside an isolated chamber and there is clearly a need to perform additional experimental work in order to validate the model applicability and accuracy in real settings.

2. *How to construct a predictor of TCP throughput using information from network, MAC*

and physical layers?

In this thesis an empirical model of TCP throughput for multi-hop wireless networks is presented. The main difference of the proposed approach from those previously reported in the literature is that our model uses adjustable parameters at different communication layers and parameters of the communication context directly measurable before the actual start of the data transfer. The model uses transmission rate at the physical layer, number of wireless hops and the maximum size of TCP segment as input parameters and predicts TCP throughput with 98 - 99% accuracy. Already in this form the model can be used for practical cross-layer optimization of the TCP throughput.

3. *How well do commonly used simulators reflect the reality with their standard empirical radio modeling capabilities?*

   It was found that simulations are roughly matching with test-bed results for single flows, but clearly deviate from test-bed results for concurrent flows. The mismatch between simulations and test-bed results is due to imperfect wireless propagation channel modeling. This work reveals the importance of validating simulation results when studying single channel multi-hop wireless network performance. It further emphasizes the need for validation when using empirical radio modeling for more complex environments such as corridors.

1.4.1 Future work

Firstly, more efforts should be spent to increase the accuracy of the prediction of the aggregated traffic intensity by using more sophisticated models as well as by choosing appropriate dimensions of the working and prediction windows. Here one should make a trade-off between the prediction accuracy and the computation time of the model. The approach proposed in this thesis could be used to adjust the parameters of the MAC layer (e.g. size of contention window, retransmission strategy, etc.), in order to minimize the packet collision probability. The design of such an optimization process is a complex task. Further development of these issues is a subject for our future investigations.

The proposed TCP throughput model uses three parameters from transport, MAC and PHY layers as input parameters: the maximum size of TCP segment, number of wireless hops and transmission rate. Already in this form the model can be used for a practical cross-layer optimization of the TCP throughput. However, from the rich experience collected in the research community on the analysis of TCP behavior in multi-hop wireless networks it is known that the number of cross-layer parameters affecting the TCP performance is large. Therefore, there is a need to continue the development of the presented material by identifying new significant adjustable parameters and parameters of the communication context and considering more complex scenarios.

Comparative study between the performance measurements in a single channel multi-hop wireless network test-bed and the corresponding measurements obtained from the popular network simulators ns-2 and ns-3, that was presented in this thesis, exposed the definite mismatch.There is, therefore, a strong need to improve the network simulators accuracy by deterministic wireless channel modeling, for example based on ray tracing techniques or empirical radio modeling.

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Paper A

On passive characterization of aggregated traffic in wireless networks

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On passive characterization of aggregated traffic in wireless networks

Anna Chaltseva and Evgeny Osipov

Abstract

We present a practical measurement-based model of aggregated traffic intensity on microseconds time scale for wireless networks. The model allows estimating the traffic intensity for the period of time required to transmit data structures of different size (short control frames and a data packet of the maximum size). The presented model opens a possibility to mitigate the effect of interferences in the network by optimizing the communication parameters of the MAC layer (e.g. size of contention window, retransmission strategy, etc.) for the forthcoming transmission to minimize the packet collision probability and further increase network's capacity. We also discuss issues and challenges associated with PHY-layer characterization of the network state.

1 Introduction

Interference from external sources (noise) as well as long range interferences caused by distant communications on the same radio channel are the main reasons for the unstable performance in wireless networks in general and those built upon the IEEE 802.11 standard in particular. Several techniques have been developed so far for mitigating the effect of interferences. Among them the most effective ones are smart antennas with power control on the physical layer [1] and contention resolution type of techniques on the MAC layer and above [2, 3, 4]. The later type of solutions in many cases require the knowledge of characteristics of aggregated traffic, which includes spatial distribution of data flows [5], density of active users [6, 7], queue occupancies [8, 9], etc. In most of the cases these characteristics are derived using the statistics of completely received and decoded data packets and control frames. This adds obvious difficulties to the accurately characterization of the network state since packets from the nodes located at the border of the communication range cannot be decoded correctly.

In this article we present the results of our work on the passive characterization of the aggregated traffic on micro- and millisecond's time scale using time series of the signal strength measured at the physical layer. Figure 1 illustrates the main idea of this article. The recorded time series of the signal strength are used to model the traffic arrival process during (discrete) time interval $[t-n,t]$. The model's outcome is used to predict an aggregated *traffic intensity* during time interval $[t,t+k]$ needed to send a pending for transmission data packet on the MAC layer. If the approach is successful the predicted in this way traffic intensity could be used to adjust the parameters of the MAC layer (e.g. size of contention window, retransmission

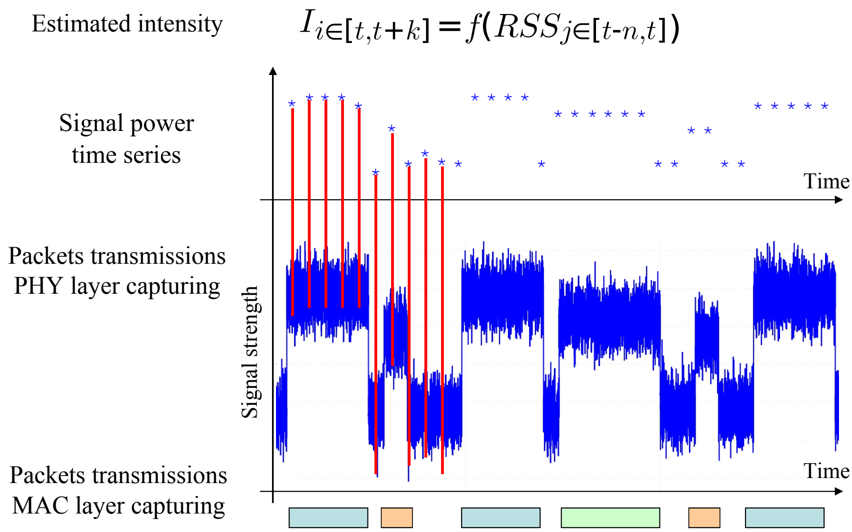


Figure 1: Approach taken in this article.

strategy, etc.), so to minimize the packet collision probability. This optimization process falls however outside the scope of this work and will be reported elsewhere.

Our major results are twofold. On the positive side we show that the statistics collected at the physical layer do not behave randomly and it is valid to use this information for characterization of the aggregated traffic in the vicinity of a wireless transmitter. For this purpose we propose a Markov based model which allows to predict the traffic intensity on micro- and millisecond's time scale. While showing the feasibility of the micro-scale traffic characterization we conclude that more efforts should be spend to increase the accuracy of the prediction as well as developing mechanisms for using this information to improve the performance of next generation cognitive MAC protocols.

The article is organized as follows. Section 2 presents the research methodology. The overview of the related work in done in Section 2.1. The passive estimation of traffic intensity including the description of experiments, data analysis, modeling, and the assessment of the accuracy is presented in Section 4, which is the main section of this article. Section 5 concludes the article.

2 Methodology

Our approach follows from the rich experience collected in the wired networks research community on characterization and modeling of the aggregated IP traffic. Traffic characterization by observing the packet arrival process and a packet size distribution was well explored in wired networks [10, 11, 12]. The major difference when analyzing an aggregated traffic on a

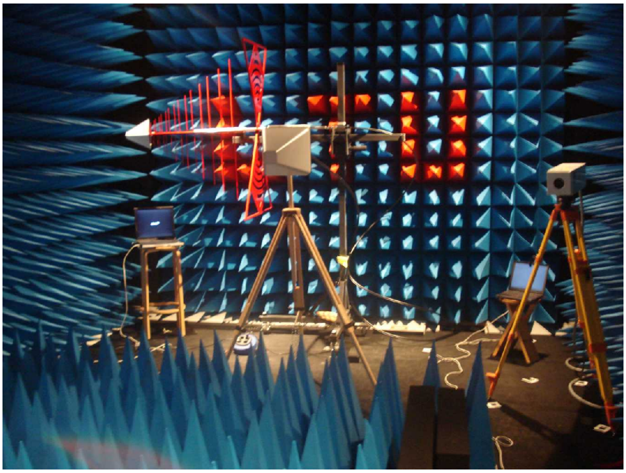


Figure 2: The radio isolated chamber.

wired bottleneck link from doing so on a wireless link is in the broadcast nature of the later. At a wireless receiver packets transmitted by nodes in the same radio range may not be correctly decoded due to bit errors caused by interferences.

The main hypothesis of our work is that it is possible to derive a PHY-layer characterization of the aggregated traffic on a wireless link by statistical analysis of time series of the received signal strength. Our methodology for verification of the hypothesis consists of three phases: data gathering; randomness and correlation analysis; and modeling and assessment.

Data gathering: All data for further analysis and modeling were obtained in a controllable manner in a radio isolated chamber shown in Figure 2. We experimented with traffic of different intensities and used a spectrum analyzer to accurately record the signal strength time series with microsecond's sampling time. The detailed description of the experiments follows in Section 4.1.

Randomness and correlation analysis: In this phase we firstly examine a statistical dependence in the recorded time series. In other words whether we can use the physical layer's statistics for characterization of the aggregated traffic intensity. The results of the two-sample Kolmogorov-Smirnov test (presented in Section 4.2) allowed us to proceed with the analysis of nature of the statistical dependence by studying the correlation structure of the series described in the same section.

Modeling and assessment: Finally, we build a two-state Markov model of the channel occupancy and use it to predict the intensity[1] of traffic during a time interval chosen with reference to the transmission time of data structures of different length (e.g. short control

[1]Strictly speaking in this article we estimate channel utilization in time domain by relating all instances of sampled time with signal above the receiver sensitivity threshold to the duration of the predicting interval. We, however, may interpret this measure as traffic intensity since we relate the duration of the predicting interval to transmission time of a single data structure.

frames and maximum size of a data packet). The rationale for doing this step is simple, if we are able to correctly predict the channel occupancy on packet transmission time scale we may further use this result to optimize the transmissions of the pending packets.

3 Related work

The work described in this article ideologically falls into the domain of opportunistic wireless networks. Such networks adapt the transmission parameters (channel/frequency, transmission rate, transmission power, etc.) depending on the current state of the communication network (interference level, aggregated traffic load, spacial nodes distribution, etc.). There have been numbers of works based on the estimation of the channel utilization for the purpose of optimizing the MAC protocol performance [13, 14, 15]. The "h" extension of the IEEE 802.11 standard [13] defines a *Dynamic Frequency Selection* (DFS) mechanism. The main idea of DFS is to reduce the interferences between wireless nodes. It is done by estimating the current utilization of available channels based on RSSI (Received Signal Strength Indication) statistics and assuming that the estimated channel state will persist in a short-term future. Based on the estimated channel occupancy a decision on remaining on the current channel or switching to a less-utilized channel is taken. The major difference with our approach is that we predict utilization of the channel in a short-term future based on probabilistic model of past measurements. Modeling of communication channel's state based on PHY-layer measurements is a popular topic in the wireless networking research community. A large scope of works (e.g. [16] and references there in) focus on modeling of interference for off-line optimization of network performance. There are not many examples, however, of attempts for on-line prediction of future channel state for higher layers protocols optimization purposes. Most related to the topic of this article works are [14, 15]. The authors in [14] use the autocorrelation function to predict the channel state ("free" or "busy"). In this work we show that the autocorrelation function cannot provide a conclusive picture in the case of mixed traffic under high load. In [15] the authors analytically model the instantaneous spectrum availability for a system with multiple channel using partially observable Markov decision process. This work presents decentralized cognitive MAC which allows the maximization of the overall network throughput. The results of our work could be considered in some extend as a practical compliment to the later approach since we build an empirical estimator of the instantaneous (plus several milliseconds in the future) channel state.

4 Passive estimation of aggregated traffic intensity using PHY-layer statistics

In this section we develop our hypothesis of deriving PHY-layer characterization of the aggregated traffic. The subsections below describe the details of data gathering, randomness and correlation analysis as well as present the constructed model and the results of its accuracy assessment.

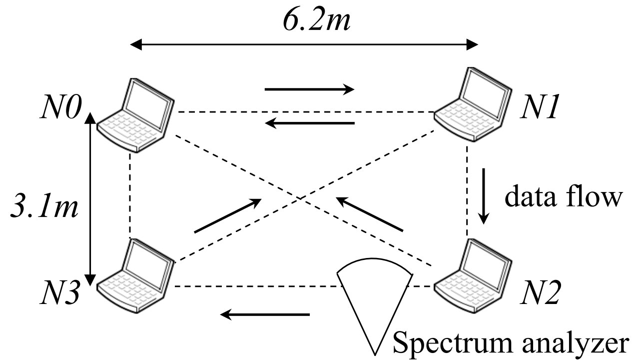


Figure 3: The test-bed topology.

Table 1: The settings on physical and MAC layers.

Parameter	Value
Physical Layer Parameters	
Transmitted signal power	18 dBm
Channel frequency	2427 MHz (channel 4)
Transmission base rate	1 Mb/s
MAC Layer Parameters	
Maximum Contention Window	1023
Short slot time	9 us
SIFS	10 us
Short preamble	72 bits

4.1 Test-bed Experiments and Data Gathering

The time series of the received signal strength were measured during a set of experiments performed on a wireless test-bed network located inside an isolated chamber (See Figure 2). The walls of the chamber are non-reflecting surfaces preventing multi-path propagation. The wireless test-bed consists of four computers equipped with IEEE 802.11abgn interfaces. All computers are running Linux operating system (kernel 2.6.32). The topology layout is depicted in Figure 3. The settings on physical and MAC layers are summarized in Table 1.

The received signal strength time series were recorded using spectrum analyzer Agilent E4440A. The recorded raw signal was sampled with 1MHz frequency. Later during the analysis phase we increased the sampling interval by trimming out the original set. We quantized the recorded signals into two levels. All samples with the signal power less than -87 dBm (the received sensitivity of the used wireless adapter) were assigned a value of 0 (zero). All measurements above this threshold were assigned a value of 1.

Traffic flows: In total 13 experiments with one, two, three, and four parallel data sessions

Table 2: Test-bed experiments scenarios.

Load	Traffic
Low	UDP $_{(100Kb/s)}$ UDP $_{(11Mb/s)}$ UDP $_{(11Mb/s)}$ TCP TCP
Medium	UDP $_{(100Kb/s)}$ TCP UDP $_{(11Mb/s)}$ TCP UDP $_{(11Mb/s)}$ UDP $_{(11Mb/s)}$ UDP $_{(11Mb/s)}$ UDP $_{(11Mb/s)}$ UDP $_{(11Mb/s)}$ UDP $_{(11Mb/s)}$ TCP TCP UDP $_{(11Mb/s)}$
High	TCP UDP $_{(11Mb/s)}$ UDP $_{(11Mb/s)}$ UDP $_{(11Mb/s)}$ UDP $_{(100Kb/s)}$ TCP TCP UDP $_{(11Mb/s)}$ TCP TCP TCP TCP TCP TCP

were performed. For further discussions we sort all experiments into three groups depending on the aggregated load (low, medium, and high) as shown in Table 2.

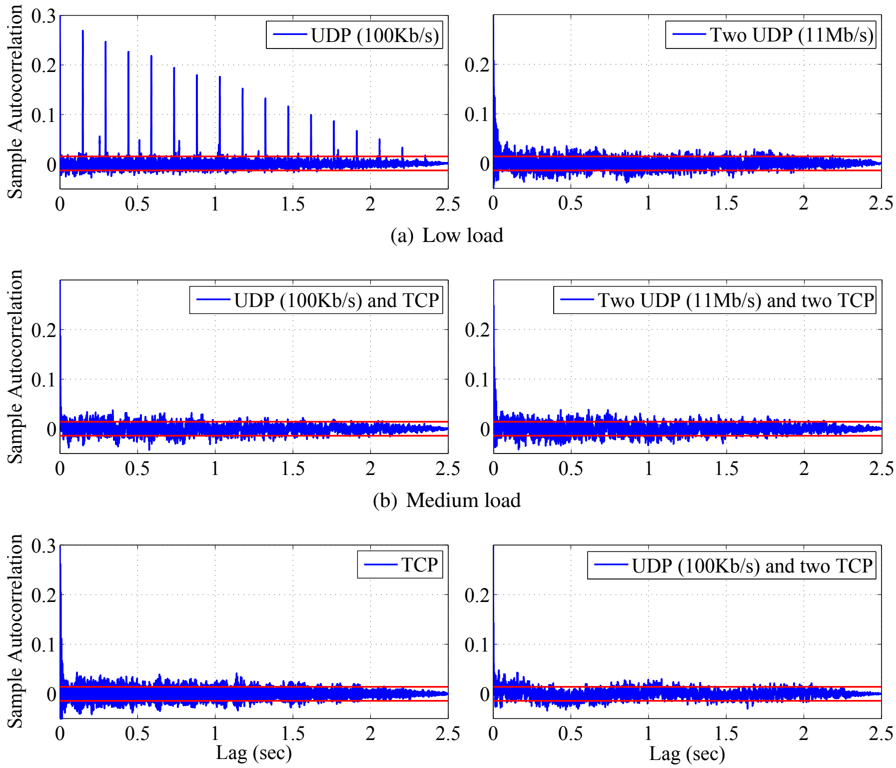
In all cases nodes were configured with static routing information in order to eliminate the disturbance caused by routing traffic. We experimented both with TCP and UDP data flows. In all experiments the payload size was chosen so to fit the maximum transfer unit of 1460 Bytes. In the case of UDP traffic we experimented with two traffic generation rates: 100 Kb/s and 11 Mb/s, to study both the unsaturated and saturated cases. The duration of each experiment was 10 seconds. To remove transient effects, only the last 2.5 seconds of the recorded signal series were used for the analysis.

4.2 Randomness and Correlation Analysis

Denote $X^C = \{x_i^C\}$ the recorded continuous time series. Let $X^R = \{x_i^R\}$ denote a reference random time series obtained by randomly shuffling[2] the original set X^C. In order to verify whether there is a statistical dependency in the original time series we performed the analysis of increments dependence [17]. The increments of time series were obtained for both X^C and X^R as $\Delta x_i^C = x_i^C - x_{i-1}^C$ and $\Delta x_i^R = x_i^R - x_{i-1}^R$ correspondingly.

In order to check the hypothesis that the recorded time series of the signal strength have a statistical dependency, the two-sample Kolmogorov-Smirnov test [18] was performed. This test compares the distributions of the values in the two given sets (the original and the reference time series). The null hypothesis is that the sets are from the same continuous distributions, accordingly, the alternative hypothesis is that the sets are from different distributions. The outcome of Kolmogorov-Smirnov test allows the rejection of the null hypothesis with 1% sig-

[2]See Python API at `http://www.python.org/`.



(a) Low load

(b) Medium load

(c) High load

Figure 4: Autocorrelation functions of the time series of the signal strength.

nificance level, i.e. there is a statistical dependency in the recorded time series. This conclusion allows us to proceed with the analysis.

Type of statistical dependency: Traffic flows in wireless networks have their specific random properties in the power domain. These properties can be summarized by the correlation structure. Traditionally, traffic models are classified either as long-range or as short-range dependent models. Short-range dependent models are characterized by relatively fast declination of the correlation function, while for long-range dependent models the correlation function decays relatively slowly and does not exceed zero. The use of long-range dependent models is more appropriate for Internet traffic modeling [19, 20]. Subsequently Markov-modulated Poisson and exponential on-off processes are commonly used to model network traffic.

Figure 4 presents the autocorrelation function of the recorded signal strength time series during 2.5 seconds. As can be expected the correlation function of one flow UDP traffic displays its periodicity (See Figure 4(a)). In the case of several flows coexisting in the wireless media, the transmission periods are not constant. Therefore, the autocorrelation functions in the case of complex traffic are not periodical. At the same time, all observed processes have

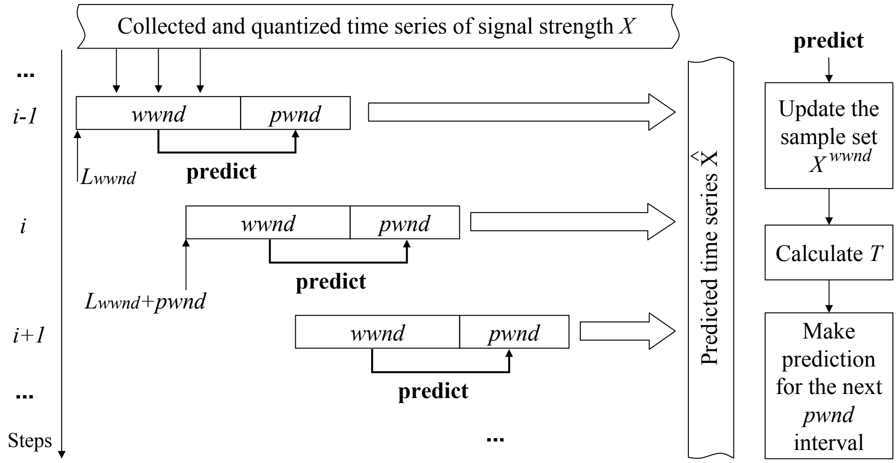


Figure 5: The model algorithm.

short-range dependence, due to the fact that the curves decay relatively fast.

4.3 Modeling and assessment

Our approach towards modeling is illustrated in Figure 5. A two-state Markov model is constructed using data collected during time interval called *working window* and denoted as *wwnd*[3]. Denote $X = \{x_i\}, x_i \in [0; 1]$ the post processed and quantized time series of X^C (See Section 4.1).

The constructed model is then used to predict the presence or absence of the signal during the immediately following time interval called *prediction window* and denoted as *pwnd*. The size of $pwnd$[4] is chosen with reference to the time of transmitting a data structure of certain length with a given transmission rate on the physical layer. We choose two values of $pwnd$ in order to illustrate our reasoning: one equals the time it takes to transmit the shortest data structure (RTS frame) with the rate 1Mb/s: $pwnd = 200$ microseconds. The other value equals the time it takes to transmit the maximum size packet (1460 Bytes) with the highest transmission rate 11Mb/s in our case: $pwnd = 1.5$ milliseconds. The rationale for choosing these values stems from the goal of this work - we want to optimize the performance of the MAC protocol prior of the transmission of a pending packet.

Two-state Markov model over $wwnd$: Denote X^{wwnd} a subset of the measured and quantized time series of the received signal strength X of size $wwnd$ expressed in number of samples. Then x_i^{wwnd} denotes the measured and quantized signal strength at sample time i. The

[3]During the course of this work we experimented with different durations of $wwnd$. It appeared that the size of $wwnd$ does not significantly affect the accuracy of the prediction. The results presented in this article are obtained using $wwnd = 0.5$s.

[4]For simplicity of presentation further on we talk about both $wwnd$ and $pwnd$ as time intervals measured in number of samples of the set of time series X.

Markov model describes the state of the channel at a particular sampling step $i+1$ based on the current state at the step i. The model is defined by a transition probability matrix T as follows:

$$T = \begin{pmatrix} P(x_{i+1}^{wwnd} = 0 | x_i^{wwnd} = 0) & P(x_{i+1}^{wwnd} = 1 | x_i^{wwnd} = 0) \\ P(x_{i+1}^{wwnd} = 0 | x_i^{wwnd} = 1) & P(x_{i+1}^{wwnd} = 1 | x_i^{wwnd} = 1) \end{pmatrix}$$

where P is an empirical conditional probability calculated over $wwnd$ number of samples.

When matrix T is calculated and the prediction of the traffic intensity (as described below) is done we shift the working window on the set of original time series X to $pwnd$ samples in the direction of time increase. This moves us to the next iteration of the modeling and prediction process, which is summarized in Figure 5.

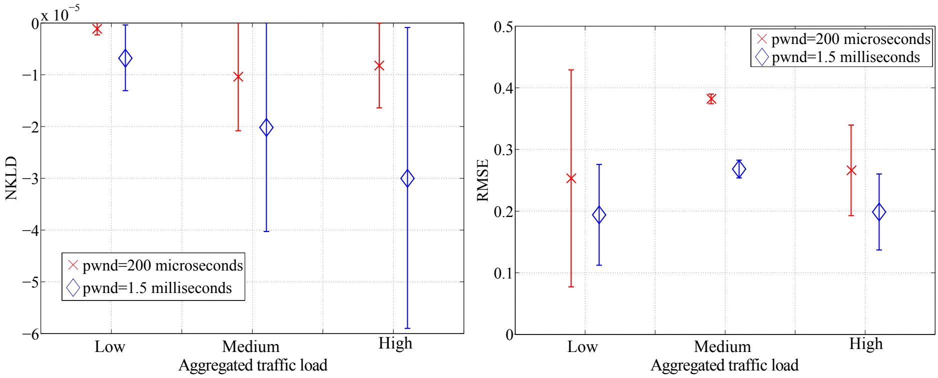
Prediction procedure over $pwnd$: The goal of the prediction process is to generate time series X^{pwnd} of the predicted signal presence. Thus $x_i^{pwnd} = 1$ indicates the presence of the signal above the receiver sensitivity threshold while the value of 0 indicates an absence of the signal at sample time i. The probabilities that during ith position of $pwnd$ there will be transmission or not are taken from the matrix T depending on the channel state at time $i-1$. After the probabilities are determined for position i of $pwnd$ we generate an actual value (1 or 0) using conventional technique for generating random numbers from a given distribution. This procedure is then repeated for all positions inside the $pwnd$.

4.4 Assessment of the quality and accuracy of the model

The quality of the model was evaluated by the analysis of the model's performance using normalized Kullback-Leibler divergence. The Kullback-Leibler divergence is a non-symmetric measure of the distance or the relative entropy between two probability distributions $Pr[X]$ and $Pr[\hat{X}]$ [21]. This statistical metric (1) is used to measure how the distribution of the set produced by a stochastic model ($Pr[\hat{X}]$) is different from the distribution of the original stochastic process $Pr[X]$.

$$D_{KL}(Pr[X]||Pr[\hat{X}]) = \sum_i Pr[X]_i * log \frac{Pr[X]_i}{Pr[\hat{X}]_i} \tag{1}$$

The smaller is the value of $D_{KL}(Pr[X]||Pr[\hat{X}])$ the closer the distributions $Pr[X]$ and $Pr[\hat{X}]$ are. In the case when $D_{KL}(Pr[X]||Pr[\hat{X}]) = 0$ the two distributions are identical. To calculate the normalized Kullback-Leibler distance the following formula was used: $\bar{D}_{KL}(Pr[X]||Pr[\hat{X}]) = \frac{D_{KL}(Pr[X]||Pr[\hat{X}])}{H(Pr[X])}$ where $H(Pr[X])$ is the entropy of a random variable with the probability mass function $Pr[X]$. $H(Pr[X]) = \sum_i Pr[X]_i * log \frac{1}{Pr[X]_i}$.



(a) NKLD for the proposed model.

(b) The proposed model accuracy.

Figure 6: Assessment of the quality and accuracy of the model.

Figure 6(a) shows the correspondent graphs of $\bar{D}_{KL}$ for the proposed model. We conclude that the model has satisfactory quality since the distance between the probability distributions of the measured time series and the predicted ones is in the oder 10^{-5}.

Model Accuracy: The accuracy of the model was evaluated with respect to its ability to predict traffic intensity over one $pwnd$ interval, denoted as ξ^{pwnd} (2). The results are presented in Figure 6(b).

$$\xi_j^{pwnd} = \frac{\sum\limits_{i=1}^{pwnd} x_i^{pwnd}}{pwnd} \tag{2}$$

The predicted intensity over one $pwnd$ interval is denoted as $\hat{\xi}_j^{pwnd} = \frac{\sum_{i=1}^{pwnd} \hat{x}_i^{pwnd}}{pwnd}$, where $j \in [1, N]$ and N is the number of $pwnd$ intervals in X and $\hat{X}$.

As the result of calculation of ξ and $\hat{\xi}$ over the original and predicted time series we obtain two sets of intensity $\Xi = \{\xi_j^{pwnd}\}$ and $\hat{\Xi} = \{\hat{\xi}_j^{pwnd}\}$ of measured and predicted intensities on $pwnd$ chunks of the time series X and $\hat{X}$ correspondingly.

We use the root-mean-square error metric to assess the differences between Ξ and $\hat{\Xi}$ (3).

$$RMSE = \sqrt{\frac{\sum\limits_{i=1}^{N} (\xi_i - \hat{\xi}_i)^2}{N}} \tag{3}$$

Figure 6(b) illustrates the accuracy of the model for different aggregated traffic loads and different values of $pwnd$. The plot is obtained by assessing the model's accuracy using three different initial positions for $wwnd$ and correspondingly $pwnd$ in the original set of time series X. From Figure 6(b) we observe that the accuracy of the model is substantially lower for the

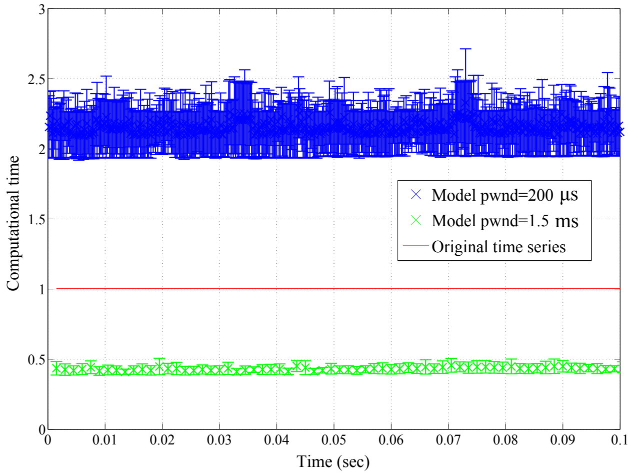


Figure 7: The computation time of the model.

short *pwnd* (200 microseconds). Although for some parts of traces with low traffic intensity the model introduced 10% error, the average error for all traffic loads ranges between 0.25 and 0.4. On the other hand for the larger *pwnd* the average value never exceeds 0.3 for all traffic loads. In particular in the case of high traffic load our models shows 0.2 prediction error.

Computation time: In order to assess the computation time of the model we timed the execution of operations for constructing the transition matrix and the prediction procedure for different values of *pwnd*. The time measurements were performed on Lenovo ThinkPad T61 computer with Intel T7300 Core 2 Duo processor, 2GB RAM and running Ubuntu 10.04 LTS operating system. Figure 7 plots the results of the measurements normalized to the duration of corresponding *pwnd*. From the figure one could immediately observe that the choice of *pwnd* size is essential. The computation time of the model is almost twice higher than the duration of the smallest *pwnd* (200 microseconds) . On the other hand it is twice less than the duration of the larger *pwnd* (1.5 milliseconds). The implications of this observation are discussed in Section 5.

5 Conclusions

In the previous section we presented a practical measurement-based model of the aggregated traffic intensity on microsecond's time scale for wireless networks. The model allows estimating the traffic intensity for the period of time required to transmit data structures of different sizes (short control frames and a data packet of the maximum size). The resulting model opens a possibility to mitigate the effect of interferences in the network by optimizing the parameters of the MAC layer for the forthcoming transmission based on the predicted aggregated traffic intensity based on short-term historical data. The presented model is based on the collected statistic in the wireless test-bed network located inside an isolated chamber and there is clearly a need in additional experimental work in order to validate the model applicability and accuracy in real settings.

Our major conclusion is twofold. Firstly, more efforts should be spend to increase the accuracy of prediction by using more sophisticated models as well as choosing the appropriate dimensions of the working and prediction windows. Here one should make a trade-off between the prediction accuracy and the computation time of the model. Secondly, we foresee that on micro- or millisecond's time scale even the best models would introduce significant error to the predicted traffic intensity. It is unrealistic to expect that aggregated traffic could be very accurately characterized solely based on samples of radio signal. One however still may use this information in more sophisticated cross-layer decision mechanisms. Further development of these issues is a subject for our ongoing and future investigations.

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PAPER B

Empirical Predictor of TCP Throughput on a Multi-hop Wireless Path

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Empirical Predictor of TCP Throughput on a Multi-hop Wireless Path

Anna Chaltseva and Evgeny Osipov

Abstract

This paper addresses a question of predicting TCP throughput over a multi-hop wireless path. Since it is useful for a variety of applications it is desirable that TCP throughput prediction technique introduces low-overhead while avoiding active measurement techniques. Analytical derivation of the throughput predictor for multi-hop wireless networks is difficult if not impossible at all due to complex cross-layer dependencies. In this article we statistically analyze the significance of parameters on physical, MAC and transport layers in a multi-hop wireless chain and empirically derive a practically usable throughput predictor. The resulting model allows prediction of the throughput with less than 2% error.

1 Introduction

Multi-hop wireless networks are known for their highly variable and unstable performance. Being able to accurately predict the performance network protocols prior to the start of the actual communication session would provide an essential input for various optimization processes, e.g. selection of an optimal multi-hop route, setting parameters for traffic shapers, configuring appropriately parameters of the MAC protocol etc. In the case of TCP based communications the correct prediction of the throughput would prevent such problems as connection migration delays, packet reordering, and re-initialization of the congestion window.

Several well-established approaches for predicting TCP throughput in the wire-line Internet exist [1]. All these approaches fall into either of two classes: formula-based or history-based. Formula-based prediction relies on mathematical models that express the TCP throughput as a function of the characteristics of the underlying network path (i.e. RTT, loss rate). The history based approaches use standard time series forecasting methods based on a history of throughput measurements from previous TCP transfers on the same path. In the case of multi-hop wireless networks history-based predictions have little sense due to high operational dynamics of these networks (node mobility, dynamic interferences etc.). As for the formula-based predictors, mathematical models for TCP throughput are typically based on certain assumptions that make the interpretation of their parameters difficult in reality. For example, estimating the packet loss rate parameter in the traditional "square root" model [2] using a periodic ping-based measurement would introduce a significant error in the prediction as it can be an order of magnitude different from the packet loss rate experienced by the flow due to self-contention on the multi-hop path or due to congestion.

We intend to obtain a practically useful TCP throughput predictor (hereafter referred to as "predictor" or "model" interchangeably) as a function of:

- *Adjustable parameters of protocols on different communication layers*, for example the maximum segment size on the transport layer, number of hops on the network layer (this parameter is "adjustable" when multi-path routing is available), size of contention window or number of retransmission attempts on the MAC layer, and transmission rate on the physical layer;
- *Characteristics of design-imposed and runtime communication context*, for example relative signal-to-interference values at nodes, etc.

Deriving such a model is an ambitious task. The large number of model parameters and complex interdependencies do not allow for analytical treatment of the problem and, therefore, make an empirical derivation challenging. In this paper we focus on the empirical throughput prediction of a bulk TCP transfer for a *single* flow in IEEE 802.11b-based multi-hop wireless chain prior to starting the actual data exchange. The contribution of this paper is thus twofold. Firstly, we present a two-stages methodology for empirical derivation of the target model. Secondly, we empirically derive a so far three dimensional variant of the cross-layer TCP throughput model as a function of gross physical layer transmission rate, number of wireless hops traversed by the flow and MSS. Our model allows practical prediction of TCP throughput with less than 2% error.

On the one hand the results presented in this paper can be *directly* used for boosting TCP performance in multi-hop wireless networks as described in [3]. On the other hand, however, the presented approach should be considered as *work in progress* towards deriving advanced TCP throughput predictor for realistic scenarios with more complex topologies and in the presence of cross traffic.

The paper is structured as follows. We outline the modeling process in Section 2. Section 3 elaborates the details of the performed experiments. The significance analysis and TCP throughput modeling is presented in Section 4. Section 5 concludes the paper.

2 Motivation and solution outline

The motivation for developing the model described in this article particularly stems from the work presented in [3]. There the authors adapted the max-min fairness framework from the wire-line Internet to the specifics of multi-hop wireless networks and suggested practically implementable mechanisms which enforce the fairness model in real networks. The two major components of the adaptive distributed capacity allocation scheme for multi-hop wireless networks are: (a) The usage of an ideal throughput achieved by a multi-hop TCP flow for characterizing the boundary load of a geographical region traversed by the session and (b) the rate throttling mechanism for reducing the output rate at sources of TCP sessions in order to control the load in their bottleneck regions. The major improvements achieved by the suggested mechanism of throttling the output rate at ingress nodes are an increase in total network throughput and almost perfect fairness.

2.1 Related work

Previous modeling of TCP throughput has generated a diverse set of results. A good overview and an extensive analysis of available TCP throughput prediction approaches is presented in [1]. One of the most common predictors which is largely used in the Internet is the “square root” model (or PFTK predictor) [2]. In wireless networks several attempts to analytically model TCP throughput were undertaken during the last decade [4], [5], [6]. It is commonly understood that capturing the cross-layer nature of wireless communications is far from being simple. Even with some simplified assumptions the resulting models are too complex to be applied in practice [7]. The works in [8], [9] use an approach of empirical TCP modeling. While these papers present fundamental observations on the TCP behavior in multi-hop wireless scenarios, practically usable TCP throughput predictor remains to be discovered. The uniqueness of the modeling approach presented in this paper comes from the nature of parameters included in the model. Our model binds the adjustable parameters of protocols on different communication layers on the one hand and directly measurable characteristics of the communication path on the other. In this way, the throughput could be predicted without the need of estimating parameters during the actual message exchange.

2.2 Our approach

We seek the TCP throughput model in *a general* form (1), where R_{PHY} is the gross data rate on the physical layer and $f(\overrightarrow{P_{ENV}}, \overrightarrow{P_{MAC}}, \overrightarrow{P_{NET}}, \overrightarrow{P_{TRAN}})$ is the rate reduction coefficient. This coefficient is a function of parameters on the physical, MAC, network, transport layers and $\overrightarrow{P_{ENV}}$ is a vector of characteristics of particular operating environment.

$$\hat{R} = R_{PHY} \cdot f(\overrightarrow{P_{ENV}}, \overrightarrow{P_{MAC}}, \overrightarrow{P_{NET}}, \overrightarrow{P_{TRAN}}). \tag{1}$$

From the rich experience collected in the research community on the analysis TCP behavior in multi-hop wireless networks it is known that the number of cross-layer parameters affecting the TCP performance is large. It is also known that not all of these parameters, though, place significant effect on the overall system performance. Moreover, involving unnecessary parameters in the cross-layer optimization process and at the end an implementation of the cross layer architecture may lead to a cumbersome solution with to a large extent unpredictable behavior [10].

Determining the optimal subset of parameters statistically significant for optimization constitutes the first phase of our methodology. At this step we perform 2^n factorial design where n is the number of candidate factors to be included in the the target model. We use F-test to evaluate the significance of chosen parameters.

In the second phase of our methodology we perform iterative curve fitting on the parameters with the highest statistical significance. In each iteration we choose a parameter with the highest significance, perform curve fitting and evaluate the accuracy of fitting using a coefficient of multiple determinations. We repeat the procedure for all significant parameters.

In this work we apply the methodology on a special class of multi-hop networks - a wireless chain with single TCP flow. The rationale for choosing this class of networks is twofold.

TCP/IP Layer	Physical	MAC	Network	Transport
Parameters	Data rate (R_{PHY})	Minimum contention window size (CW_{min})	Number of hops (N_{hops})	Maximum segment size (MSS); maximum congestion window ($CWND$)

Table 1: Parameters on different communication layers potentially affecting the TCP throughput selected for significance analysis in this work.

Firstly, our target is to create a model for an ideal throughput of TCP bulk transfer without interferences inferred by the cross traffic [3]. Secondly, already with these settings applying our model is both effort and time consuming. Overall, we follow a bottom-up approach by first modeling the simplest case and then extending the model by gradually adding complexity of the scenarios.

2.3 Highlights of the contribution

For the significance tests in this work parameters reflected in Table 2.3 were selected. Note that the table does not present a complete list of parameters on different layers. For this work we only selected those with the highest relevance to the considered scenario.

In total we performed 24000 simulation runs to collect the necessary statistics for the significance analysis of the four chosen factors. The most interesting result from the significance analysis is that imposing an artificial limit on the size of TCP congestion window does not significantly affect TCP throughput in the particular scenario. This result differs from previously published findings in [8] suggesting to clamp $CWND$ depending on the number of hops as $\frac{3 \cdot N_{hops}}{2}$. However, this finding *is not* a contradiction to previous analysis, but shows that there is a complex dependency between $CWND$ parameter and characteristics of the communication context.

As a result of iterative fitting we obtained a three-dimensional variant of the model (2), where $\overrightarrow{\alpha}$, $\overrightarrow{\beta}$ and $\overrightarrow{\gamma}$ are vectors of scalar values for each considered physical layer transmission rate.

$$\hat{R}(R_{PHY}, N_{hops}, MSS) = R_{PHY} \cdot \frac{MSS + \overrightarrow{\alpha}}{\overrightarrow{\beta} \cdot N_{hops} - \overrightarrow{\gamma}}. \qquad (2)$$

The coefficients in vectors $\overrightarrow{\alpha}$, $\overrightarrow{\beta}$ and $\overrightarrow{\gamma}$ can further be expressed as functions of other parameters. Determining these parameters is left outside the scope for this paper and will be considered in our future work. Our model allows practical prediction of TCP throughput with less than 2% error.

Table 2: Factors and chosen levels in factorial design.

Factors	N_{hops}		MSS (Bytes)		$CWND$ (segments)		CW_{min}	
Levels	Low	High	Low	High	Low	High	Low	High
Values	1	2	100	200	2	3	15	30
	3	4	500	600	6	7		
	9	10	900	1000	10	11		
			1360	1460	14	15		
					18	19		

3 Description of experiments and simulation setup

For the analysis of statistical significance of model parameters we performed factorial design as one of the most suited techniques for such purposes [11]. In this technique independent variables of interest (or *factors*) are assigned discrete values (or *levels*). The factorial design is a strategy where experiments are performed with all possible combinations of the factors' levels. We decided to perform the analysis with two levels for each factor ("low" and "high"). This number allows reducing the number of simulation runs while keeping good statistical accuracy of the analysis. Analyzing only two values for each factor is, however, not enough for the identification of the factor's significance. For this reason N_{hops} factor was analyzed with three pairs of levels, MSS with four pairs, $CWND$ with five pairs as indicated in Table 2. The significance of CW_{min} factor was analyzed with one pair of values. Each experiment was repeated 5 times randomly seeding the random number generator at each iteration. In total 24000 ($2^4 \cdot 3 \cdot 4 \cdot 5 \cdot 1 \cdot 5$) independent factorial designed experiments were performed.The response from each run is the throughput in kilobits per second which was computed as the amount of data received by the sink node divided by the total transmission time.

3.1 Simulation setup

The network topology used in our experiment is a static wireless chain depicted in Figure 1. The nodes were placed on distances equivalent to the transmission range of the wireless interface at a given physical layer data rate. A single wireless channel is shared by all nodes in the network. Static routing was used in order to avoid interferences imposed by the routing traffic. The test flow originated at Node 1 and traversed variable number of hops to the last node in the chain which was the sink node for the monitored flow. We used TCP Newreno and an FTP application which constantly generated traffic during each simulation run. We used network simulator ns-2.33 [12] to perform the experiments. Prior to the experiments we performed careful calibration of the network simulator parameters in order to achieve as close to the reality performance figures as possible. For this we configured the simulator with parameters of real IEEE 802.11b network interfaces which are used in our wireless mesh test-bed. Table 3 summarizes the used settings. In order to verify the correctness of the simulation settings we compared the results from the simulations to the performance of the bulk transfer in a real

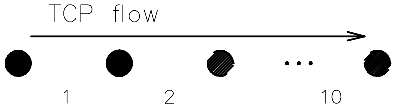

Figure 1: The experimental chain topologies.

Table 3: Simulation parameters.

Parameter	Value
Physical Layer Parameters	
Carrier sensing threshold	-115 dBm
Reception threshold	-72 dBm
Transmitted signal power	15 dBm
Channel frequency	2437e6 (channel 6)
Base TX rate	1 Mb/s
Data rate	2, 5.5, 11 Mb/s
MAC Layer Parameters	
Maximum Contention Window	1023
Short slot time	9 us
SIFS	10 us
Short preamble	72 bits
RTS/CTS	off

multi-hop test-bed deployed in our lab. As Table 4 indicates we achieved good simulations accuracy especially on larger hop counts.

4 Statistical significance and empirical throughput modeling

In factorial analysis F-test is used to evaluate the significance of a factor. The null hypothesis of the F-test is that the factor would have a zero coefficient when added to a linear model. The decision about the validity of the null hypothesis is taken by inspecting the p-value of the

Table 4: Results of calibration of network simulator parameters: TCP throughput (in kb/s) measured in simulations and in real multi-hop test-bed.

hops	1	3	6
Simulations	5041.4	1681.2	836.3
Measurements	3870.0	1260.0	870.0
$\|\Delta\|$	1171.4	421.2	33.7

Table 5: Maximum and minimum impacts of considered factors in regression models where all factors were significant (20% of all regressions).

Factors	N_{hops}		MSS		$CWND$		CW_{min}	
R_{PHY} Mb/s	min	max	min	max	min	max	min	max
1	-1093	-52	998	12700	-38	-3.7	-3.7	265
2	-2059	-83	1897	29070	-68	-3.6	-3.6	492
5.5	-4694	-135	8209	87120	-133	-8.7	-8.7	630
11	-7448	-161	11027	17746	-180	-6.6	-6.6	222

test. The p-value is defined as the smallest level of significance that would lead to rejecting the null hypothesis [11]. A significance level of the test (α-level) is a probability of rejecting the null hypothesis when in fact it is true. Accordingly factors which p-values are lower then the defined α-level are considered as significant. Usually a significance level equal to 0.05 is considered as an acceptable error level.

The F-test is based on the assumption of normality and independence of the residuals from an identified linear regression model. In our analysis the normality assumption was checked by evident results from Jarque-Bera hypothesis test of composite normality. The independence is achieved by the experiment design presented in the previous section.

Applying factorial analysis to experimental data led to identify the following factors as significant: N_{hops} and MSS with confidence 95% (α-level equals 0.05). We observed that factors CW_{min} and $CWND$ were significant only in some small part of the experiments. Table 5 demonstrates the minimum and maximum impacts of the factors shown as coefficients in linear regression models where *all* factors were significant for the particular physical layer transmission rate. We observe that even when CW_{min} and $CWND$ factors are significant, their impact is considerably smaller compared to the impact from N_{hops} and MSS factors. Therefore, for the TCP throughput modeling we decided to continue only with N_{hops} and MSS, the factors with the most evident significance in *this particular* scenario. We, however, highlight that CW_{min} and $CWND$ should not be disregarded from further modeling of more complex scenarios as their impact could became more significant in other settings [8]. We, however, leave the development of this issue for our future work.

4.1 Iterative empirical modeling of TCP throughput

In this section we present the results of an iterative throughput modeling based on three selected parameters: number of wireless hops (N_{hops}), TCP maximum segment size (MSS) and physical layer transmission rate (R_{PHY}).

Two dimensional throughput model: Fitting N_{hops} and R_{PHY} parameters.

The plots of the measured TCP throughput $R_{measured}$ in Figure 2 suggest choosing a reciprocal function of number of hops in form $\frac{1}{a \cdot N_{hops}+b}$ as the target function for TCP throughput. We

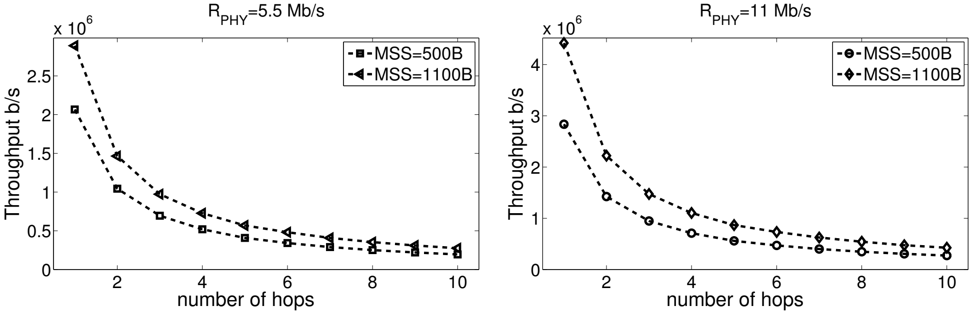

Figure 2: TCP throughput measured in simulations for R_{PHY}=5.5 and 11Mb/s and selected values of MSS versus number of hops.

performed $|\mathbf{R_{PHY}}| \times |\mathbf{MSS}|$ nonlinear regressions where $|\mathbf{R_{PHY}}|$ and $|\mathbf{MSS}|$ are cardinality of vectors of physical layer transmission rates and MSS sizes used in the experiments correspondingly. In this way we estimated matrices of coefficients $\mathbf{A}$ and $\mathbf{B}$ for each permutation of the rate and the MSS values. The non-linear regression was transformed to the linear one by fitting $\frac{1}{R_{measured}}$ values to first order polynomial $a \cdot N_{hops} + b$ using the method of least squares. After that in all models with the determined coefficients we extracted the values equal to the corresponding physical layer data rate and obtained elements of the matrices of coefficients $\mathbf{A}$ and $\mathbf{B}$ as $\frac{1}{R_{PHY}} \cdot a_{i,j}$ and $\frac{1}{R_{PHY}} \cdot b_{i,j}$ correspondingly. By this we obtained the two-dimensional model for TCP throughput (3).

$$\hat{R}(R_{PHY}, N_{hops}) = \frac{1}{\frac{1}{R_{PHY}} \cdot (\mathbf{A} \cdot N_{hops} - \mathbf{B})} = R_{PHY} \cdot \frac{1}{\mathbf{A} \cdot N_{hops} - \mathbf{B}}. \quad (3)$$

The coefficient of multiple determination was used as a measure of the prediction accuracy of the model. The estimated values for the coefficients $a_{i,j}$ and $b_{i,j}$ for the different physical layer transmission rates (index i) and the selected MSS sizes (index j) as well as the calculated R^2 values for (3) are reflected in Table 6. The calculated R^2 values shows that the predictive ability of the model is better then 96%.

Table 6: Values of coefficients a_1 and b_1 in two-dimensional model with corresponding R^2 values.

	A						**B**						R^2
MSS, B	100	500	900	1100	1300	1460	100	500	900	1100	1300	1460	
1 Mb/s	3.23	1.84	1.59	1.55	1.49	1.4	1.06	0.50	0.37	0.36	0.31	0.34	0.96
2 Mb/s	3.99	2.04	1.72	1.64	1.58	1.54	1.04	0.45	0.35	0.33	0.31	0.29	0.97
5.5 Mb/s	6.78	2.82	2.17	2.00	1.88	1.83	1.36	0.52	0.39	0.32	0.27	0.30	0.98
11 Mb/s	11.03	4.03	2.86	2.58	2.38	2.25	1.28	0.45	0.28	0.28	0.24	0.19	0.99

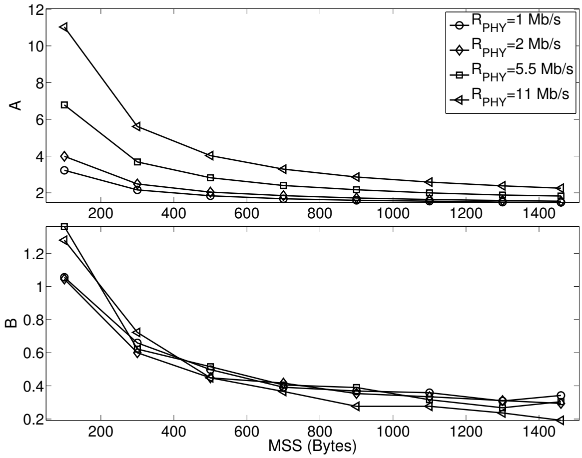

Figure 3: Coefficient a_1 and b_1 versus MSS for different physical layer data rates.

Three dimensional throughput model: Fitting the MSS parameter.

In the next iteration of fitting we extended model (3) as follows. The matrices of coefficients $\mathbf{A}$ and $\mathbf{B}$ are functions of MSS for different physical layer transmission rates: $\hat{R}(R_{PHY}, N_{hops}, MSS) = R_{PHY} \cdot \frac{1}{f_1(MSS) \cdot N_{hops} + f_2(MSS)}$.

Based on the shape of plots of the estimated $\mathbf{A}$ and $\mathbf{B}$ values as a function of MSS shown for a given transmission rate in Figure 3 we again selected a reciprocal function as a candidate for fitting: $f_1(MSS) = \frac{1}{\overrightarrow{a1} \cdot MSS + \overrightarrow{a2}}$ and $f_2(MSS) = \frac{1}{\overrightarrow{b1} \cdot MSS + \overrightarrow{b2}}$. Here $\overrightarrow{a1}, \overrightarrow{a2}, \overrightarrow{b1}, \overrightarrow{b2}$ are vectors of coefficients (for transmission rates 1, 2, 5.5, 11 Mb/s) to be estimated by linear regression on the set of previous coefficients $\{\frac{1}{a_{i,j}}\}$ and $\{\frac{1}{b_{i,j}}\}$. The result of the regression with $R^2 \geq 0.97$ accuracy are vectors:

$$\overrightarrow{a1} = \{0.30; 0.33; 0.35; 0.31\} \cdot 10^{-4}; \quad \overrightarrow{a2} = \{0.38; 0.31; 0.18; 0.10\},$$
$$\overrightarrow{b1} = \{0.19; 0.21; 0.25; 0.38\} \cdot (10)^{-3}; \quad \overrightarrow{b2} = \{0.11; 0.11; 0.09; 0.06\} \cdot (10).$$

Now, since f_1 and f_2 belong to the same class of functions we may express them as a *product* of another function $f_3(MSS) = \frac{1}{MSS+\alpha}$ of their class and multipliers β and γ, which transforms the common function f_3 to f_1 and f_2 as $f_1(MSS) = f_3(MSS) \cdot \beta$ and $f_2(MSS) = f_3(MSS) \cdot \gamma$ correspondingly (this step is illustrated in Figure 4). By doing this the target model for TCP throughput takes form (4). Note that multipliers α, β and γ are specific to the particular transmission rate and therefore in (4) the vector notation is used.

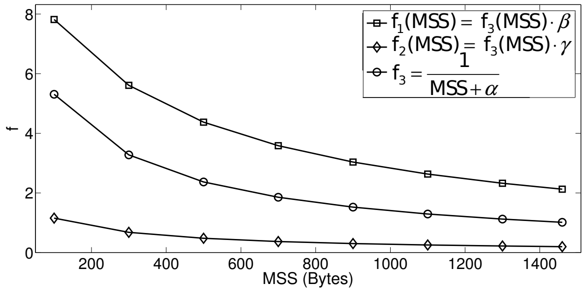

Figure 4: Functions f_1, f_2 and f_3 of MSS on the example of f_1 and f_2 model for$R_{PHY} = 11Mb/s$.

Table 7: α, β, and γ coefficients values

R_{PHY} (Mb/s)	α	β	γ	R^2
1	9834	27394	1851	0.98
2	7541	25777	1433	0.98
5.5	4458	25997	984	0.99
11	2966	30284	855	0.99

$$\hat{R}(R_{PHY}, N_{hops}, MSS) = R_{PHY} \cdot \frac{1}{f_3 \cdot (\overrightarrow{\beta} \cdot N_{hops} - \overrightarrow{\gamma})} = \\ = R_{PHY} \cdot \frac{MSS + \overrightarrow{\alpha}}{\overrightarrow{\beta} \cdot N_{hops} - \overrightarrow{\gamma}}. \tag{4}$$

We estimate the value of coefficient vectors $\overrightarrow{\alpha}$, $\overrightarrow{\beta}$ and $\overrightarrow{\gamma}$ for each considered physical layer transmission rate by performing a system of nonlinear regressions for target model (4). Due to space limitations and because we used standard methods of performing a system of regressions, we do not present the details of the regression analysis here. The values of α, β and γ obtained as the result of the regression analysis are reflected in Table 7 along with R^2 values for the accuracy of each estimated model.

The calculated R^2 values shows that the predictive ability of the model is better then 98%. Figure 5 demonstrates how well the estimated model fit the measured values of throughput in the case when $R_{PHY} = 11$ Mb/s for selected values of MSS.

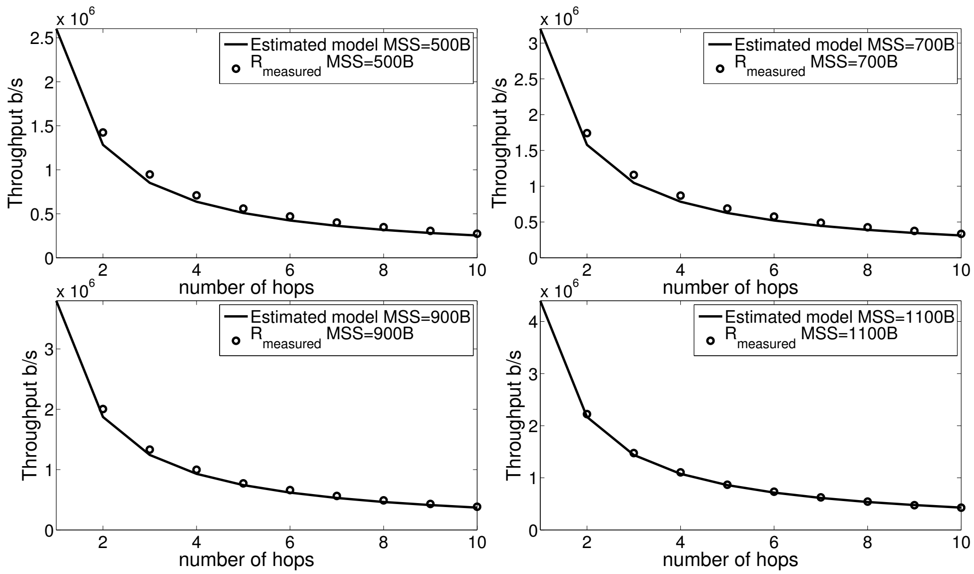

Figure 5: TCP throughput measured in simulations and predicted by the final model for R_{PHY}=11Mb/s and different values of MSS versus number of hops.

5 Conclusions

In this paper we considered a problem of empirical modeling of TCP throughput in wireless networks. The main difference of our approach from those previously reported in the literature is that our model uses adjustable parameters on different communication layers and parameters of the communication context directly measurable before the actual start of the data transfer. Since modeling of cross-layer dependencies is a complex task in this paper we presented a so far three-dimensional variant of the general model. Our model uses transmission rate at the physical layer, number of wireless hops and the maximum size of TCP segment as the input parameters and predicts TCP throughput with 98 - 99% accuracy. Already in this form the model can be used for a practical cross-layer optimization of the TCP throughput. We continue the development of the presented material by identifying new significant adjustable parameters and parameters of the communication context and considering more complex scenarios.

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PAPER C

Comparison of Wireless Network Simulators with Multi-hop Wireless Network Test-bed in Corridor Environment

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Comparison of Wireless Network Simulators with Multi-hop Wireless Network Test-bed in Corridor Environment

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Abstract

This paper presents a comparative study between results of a single channel multi-hop wireless network test-bed and the network simulators ns-2 and ns-3. We explore how well these simulators reflect reality with their standard empirical radio modeling capabilities. The environment studied is a corridor causing wave-guiding propagation phenomena of radio waves, which challenges the radio models used in the simulators. We find that simulations are roughly matching with test-bed results for single flows, but clearly deviate from test-bed results for concurrent flows. The mismatch between simulations and test-bed results is due to imperfect wireless propagation channel modeling. This paper reveals the importance of validating simulation results when studying single channel multi-hop wireless network performance. It further emphasizes the need for validation when using empirical radio modeling for more complex environments such as corridors.

1 Introduction

Nowadays most of the research in the field of wireless networking is based on network simulators. Simulators are attractive for researching network protocols and mechanisms since they allow creating controlled and reproducible environments. Creating such an environments in real test beds is both expensive and time consuming. Real production networks at the same time often do not allow to obtain repeatable data sets needed for research analysis. Various network settings and large parameter ranges can be tested through simulations at low effort since creation and modification of network scenarios as well as data gathering are easy.

In this paper we study how well simulations reflect the reality with commonly used empirical models of wireless propagation channel that requires little configuration and are memory and computationally sparse. In particular, we explore disparities between simulations in ns-2[1] and ns-3[2] and test-bed results for a multi-hop wireless network located in a corridor. This environment challenges the wireless propagation channel model present in the network simulators.

The performance of network protocols in a test-bed is affected by wireless channel properties that depend on the physical environment, location and mobility of the nodes, and the external interference. Accurate wireless channel modeling for simulations is known to be difficult. The commonly used wireless propagation channel for path loss in simulators is

[1]ns-2 NetworkSimulator. Online. Available: `http://www.isi.edu/nsnam/ns/`

[2]ns-3 Network Simulator. Online. Available: `http://www.nsnam.org`

empirically modeled, and path loss is computed depending on distance between transmitter and receiver. Consequently, accumulative interference caused by hidden terminals' concurrent transmissions, and spatial reuse ratios of test-bed network may not be correctly represented by the simulators. Due to these reasons simulation results often do not match perfectly with the test-bed results [1, 2].

The modeling of wave-guiding propagation phenomena of radio waves in corridors as well as modeling of the losses caused by reflections, diffraction and scattering of radio waves are more accurately captured by deterministic channel modeling methods [3]. The deterministic wireless channel modeling, e.g based on ray tracing techniques require the exact knowledge of location, shape, dielectric and conductive properties of all objects in the environments and it also requires extensive computational efforts for accuracy. Thus such models are site specific. In addition these models also considerably increase simulations' run time [4].

The aim of our paper is to make the wireless network researchers aware of the differences of the simulations from real wireless test-bed. The differences are mainly caused by empirically modeled wireless propagation channel of the simulators. Empirical wireless propagation channel models of the simulators are simple from implementation perspective but they do not cover all the properties of the wireless propagation channel such as losses due to reflections, diffraction, scattering and penetration of the radio waves. We demonstrate the differences between simulations and test-bed for two specific scenarios composed of single and concurrent flows transmissions over a single multi-hop path.

We find that for single flow transmissions over multiple radio links, ns-2 and ns-3 simulations roughly match the test-bed results. Deviations between simulations and the test-bed results are explained by the wireless propagation channel models used in the simulations are not accurately reflecting the accumulative interference caused by hidden terminals' concurrent transmissions and the spatial reuse ratio [3] of the test-bed network. This shortcoming of the wireless propagation channel model becomes more evident for simultaneous flows transmissions, which have higher strength of accumulative interference than single flow. Simulations indicate considerably worse matching of the throughput fairness of simultaneous flows with test-bed results, which reveals that the wireless propagation channel models of the simulators are not correctly representing the wireless channel properties in the corridors.

The article is organized as follows. Section II presents a brief overview of the background and related works. Section III presents the details and specifications of the test-bed network and experiments. Section IV gives the details of the simulation setup and also provides an overview of path loss and multi-path fading models. Section V presents the comparison of the experimental results with simulations. Section VI concludes this comparative study.

2 Background and related work

Network simulators ns-2 and ns-3 are de-facto standard simulation tools in the academic networking research community. Simulations in ns-2 are constructed with C++ code and OTcl scripts; the former provides modeling of applications, simulation nodes, communication chan-

[3] Spatial reuse ratio is the total number of concurrent transmissions accommodated in network.

nels and other mechanisms involved in networking, while the latter is used to control simulations and define additional features, for example the network topology.

Simulations in ns-3 are fully based on C++, but can also be created with Python. The ns-3 simulator was developed from scratch and cannot directly use the code developed for ns-2. Many objects are ported from ns-2 to ns-3 but not all, and hence ns-2 incorporate capabilities not present in ns-3. However, ns-3 has capabilities not implemented in ns-2 such as support for multiple interfaces on nodes, use of IP addressing and closer resemblance with the TCP/IP model, and more detailed 802.11a/b/s models.

The accuracy of wireless channel models for simulations naturally determines the quality of the outcome. It could be expected that the more detailed modeling of the IEEE 802.11 MAC protocol in ns-3 would result in more accurate results for certain network scenarios. Obviously it is expected that the simulations results may deviate from the reality. It is therefore important to understand the degree of reality reflection by the simulators.

Other studies presenting comparisons between simulations of IEEE 802.11 based networks and test-beds include [5], which presents a comparative study between an IEEE 802.11a based test-bed and three network simulators (ns-2, QualNet and OPNET). It aims to assess the relevance of these simulators in indoor and outdoor environments. The simulation results match to some extent with the test-bed. The authors highlight that tuning of physical layer parameters and selected propagation models have great impact on the results. This study is conducted for a single hop network and no comparison with ns-3 simulations is presented.

In [6] the authors present a validation study of the IEEE 802.11b MAC model in ns-3 by comparing simulations with test-bed results. The study shows that ns-3 simulations nearly match with reality after proper tuning of the devices in the test-bed. It is also shown that for mismatching between the simulation and test-bed results, simulator is not always wrong but specific selection and configuration of the devices in the test-bed can be culprit. However, in the test-bed wireless channel propagation effects on measurements are ignored because the communication between the devices is via coaxial cables.

The authors in [7] point out the disparities between a wireless network test-bed and ns-2 and Qualnet. The disparities are explored based on antenna diversity, path loss, multi-hop, transmission rate, interference and routing stability. However, ns-3 simulations have not been taken into account and intra-path interference[4] is discussed only for a single flow traffic over a linear multi-hop network.

3 Test-bed and experiments description

We built an IEEE802.11b based multi-hop wireless test-bed in an indoor corridor environment. The network consists of eight nodes placed as illustrated in Figure 1. The logical topology is a chain, the placement of nodes ensures the line-of-sight communications with the immediate neighbors. All nodes are Intel Pentium 4 based desktop PCs with 2.40 GHz processor, cache size 512 KB, RAM memory 256 MB and six USB 1.0 ports supporting the data transfer rate of 12 Mb/s.

[4] Interference between the packets of the same end-to-end flow due to hidden terminals.

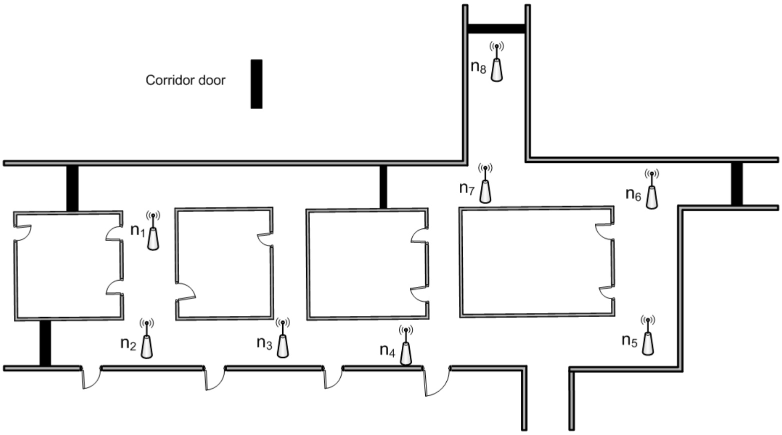


Figure 1: Test-bed: Layout of nodes in corridors.

For wireless connectivity each node is equipped with D-Link DWL-G122 wireless USB adapter[5] with an omni-directional antenna. The operating system is Linux (kernel 2.6.29) and the WLAN driver is p54[6]. At the MAC layer we switched off the options for frame fragmentation, dynamic rate adaption and disabled the RTS/CTS exchange. The transceivers operate on channel 3, the transmit power at each node was set to 18dBm, the physical channel data rate is set to 11Mb/s.

We experimented with TCP traffic generated by Iperf (version 2.0.8) traffic generator. We used TCP-Cubic configured with the default settings. The routes were configured statically in order to eliminate the effect of routing protocols on network performance [8].

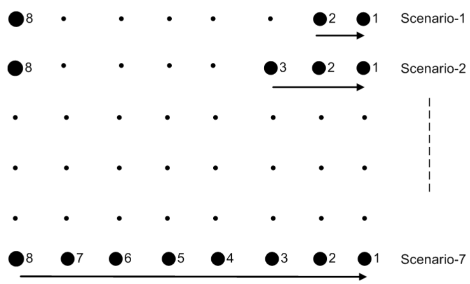
In the test-bed we conducted two types of experiments. The first experiment (further on referred to as *experiment-1*) was performed with a single flow running over a different number of hops. The second experiment (further on referred to as *experiment-2*) was conducted with multiple TCP flows running concurrently over different number of hops. To obtain the results from both experiments, we used tcpdump (version 3.9.8) to capture all the traffic generated in the network and measure the per-flow throughput.

The setup for experiment-1 is shown in Figure 2(a). The experiment consists of seven scenarios with different number of wireless hops for the monitored flow. In order to capture the effects of multi-path fading and the accumulative interference on the network performance each scenario was repeated six times by changing the position of the source and destination node along the multi-hop chain for a given number of hops. The duration of each trial is three minutes.

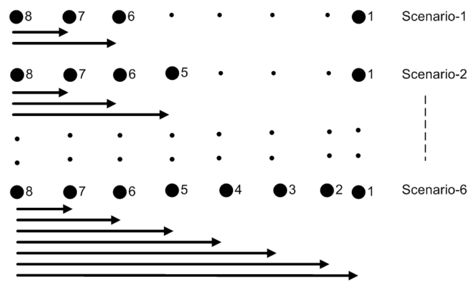
In experiment-2 (see Figure 2(b)) the layout of the nodes and the network specification had been kept the same as in experiment-1. The experiment consists of six scenarios. In all

[5]DWL-G122 High Speed 2.4GHz (802.11g) Wireless USB Adapter. Online. Available: `http://www.dlink.com/products/?pid=334`

[6]Online.Available: `http://linuxwireless.org/en/users/Drivers/p54`



(a) Layout of Experiment-1.



(b) Layout of Experiment-2.

Figure 2: Setup of experiments in the test-bed.

scenarios the traffic is alway generated from node 8. We start experimenting with two flows of one and two hops running in parallel. In each subsequent scenario we add flows as shown in the figure. As a result in the sixth scenario we experiment with seven concurrent TCP flows. We perform two trials for each scenario and record an average value of the per-flow throughput. The duration of each experiment is two minutes. The throughput values are used to compute a fairness index as explained below.

4 Simulation setup

We replicate the test-bed experiments in ns-2 and ns-3 simulators. Firstly, we configure the parameters of the simulators with the corresponding values in the test-bed. In particular, the transmission power, characteristics of the antenna and the corresponding transmission ranges are set according to the specification of the D-Link DWL-G122 wireless USB adapter. According to the device's data sheet the transmission range is set to 100 m. According to [9] the carrier sensing range in commercial wireless cards is twice or more than the transmission range.

On the transport layer we used TCP-Cubic as in the test-bed experiments. Note that while the implementation of TCP-Cubic in ns-2 is a simulator-specific, ns-3 links the real implementation from Linux via the Network Simulator Cradle (NCS).

Special attention was paid to the proper configuration of the path loss and multi-path fading models in order to reflect the radio environment of the test-bed. In the indoor environment, the propagation of radio waves is mainly affected by two types of losses: the path loss and the loss due to small and large scale fading. The small scale fading arises due to the multi-path propagation effect and the large scale fading is due to the shadowing effect. The model which closely reflects the path loss in the indoor environment is the log-distance path loss model [10]:

$$L_p = L_0 + 10n \log_{10} \frac{d}{d_0} + X_\theta. \tag{1}$$

In (1) n is the path loss distance exponent, d_0 is the reference distance (1 m), d is the distance in meters between the transmitting and the receiving nodes, L_0 is the reference path loss at the reference distance (dB), L_p is the path loss (dB) and X_θ is a log-normally distributed random variable (dB) with standard deviation σ and zero mean describing the attenuation caused by the obstacles due to shadowing effect.

Note that the value of n depends on the operating frequency and the characteristics of the propagation environment. In the case of the indoor environment, the type of the construction material and the position of the nodes within the building. In corridors due to wave-guiding propagation phenomena of radio waves, n takes values in the range $[1.3, 1.9]$ at 2.4 GHz [11, 12]. From Friis propagation loss model $L_0 = 20\log_{10}\frac{4\pi d_0}{\lambda}$ where λ is the wave length in meters.

Note that in our test-bed there is no large scale fading due to line-of-sight communication between the adjacent nodes, therefore, $X_\theta = 0$ and (1) reduces to

$$L_p = L_0 + 10n\log_{10}\frac{d}{d_0}. \tag{2}$$

However, the small scale fading exists in the corridors due to multi-path propagation. In corridors the small scale fading is described by Nakagami distribution [13, 14]. The probability density function for the Nakagami m-distribution is

$$pdf_r = \frac{2}{\Gamma(m)}\left(\frac{m}{\omega}\right)^m r^{2m-1}\exp\left(-\frac{m}{\omega}r^2\right) \quad . \tag{3}$$

In (3) $r \geq 0$ is the amplitude of the received signal, $\Gamma(m)$ is the Euler's Gamma function, $\omega = \bar{r}^2$ is the mean square received power and $m = \frac{\omega^2}{(r^2-\omega)^2}$ is the fading depth, where $m \geq 1/2$. For $m = 1$, the Nakagami m-distribution becomes Rayleigh distribution.

In ns-3 the log-distance path loss and Nakagami fading models are implemented separately. Both models can be used and configured individually. In ns-2 the log-distance path loss model is not yet implemented, however, the Nakagami fading model is implemented together with three-log-distance path loss model. The three-log-distance path loss model of ns-2 is different from the log-distance path loss model with three distance fields namely near, middle and far. Each field has different path loss exponent. For the three-log-distance model a fourth distance field is also defined from 0 to near distance, however, the loss over this field is zero. The limits of four distance fields along with their corresponding path loss exponents are explained as

$$\underbrace{0\cdots\cdots}_{0}\underbrace{d_0\cdots\cdots}_{n_0}\underbrace{d_1\cdots\cdots}_{n_1}\underbrace{d_2\cdots\cdots}_{n_2}\infty$$

So each field starts at the end of the preceding one and hence the resultant three-log-distance path loss model is a continuous function of the distance:

$$L_p = \begin{cases} 0 & d \leq d_0 \\ L_0 + 10n_0\log_{10}\frac{d}{d_0} & d_0 \leq d < d_1 \\ L_0 + 10n_0\log_{10}\frac{d_1}{d_0} + 10n_1\log_{10}\frac{d}{d_1} & d_1 \leq d < d_2 \\ L_0 + 10n_0\log_{10}\frac{d_1}{d_0} + 10n_1\log_{10}\frac{d_2}{d_1} + 10n_2\log_{10}\frac{d}{d_2} & d_2 \leq d. \end{cases} \tag{4}$$

In (4) n_0, n_1, n_2 are the path loss distance exponents and d_0, d_1, d_2 are three distance fields(meter).

The Nakagami fading model in ns-2 defines three parameters m for three distance fields as

$$\underbrace{0\cdots\cdots}_{m_0}\underbrace{d_1\cdots\cdots}_{m_1}\underbrace{d_2\cdots\cdots}_{m_2}\infty$$

The defaults values of distances and fading parameters m in ns-2 are $d_1 = 80$ meter, $d_2 = 200$ meter, $m_0 = 1.5$ and $m_1 = m_2 = 0.75$. In the test-bed the maximum distance between the adjacent nodes per hop is less than 80 meter, so ns-2 is using log-distance path loss model part of (4).

In order to find a better match of the path loss and multi-path fading with the real test-bed the simulations are conducted for five combinations of the path loss exponent $n = 1.9$ and five Nakagami fading parameters m i.e. $1.5, 1.75, 2.0, 2.25$ and 2.50. Note that doing simulations with higher values of the fading parameter m is not realistic because the higher m means stronger LOS component of the propagation model. This is not the case with the D-Link devices used in the test-bed, which are equipped with omni-directional antennas. The next section report the results of the analysis.

5 Comparative analysis

5.1 Experiment-1: test-bed vs. simulations

Figure 3 and Figure 4 show ns-3 and ns-2 simulations of experiment-1 along with corresponding test-bed results of experiment-1. As expected the TCP throughput decreases with increasing number of hops. This is because of the increase in accumulative interference due to hidden terminal problem and the decrease in spatial reuse ratio of the network due to the exposed terminal problem.

In case of test-bed results, the most severe effect of accumulative interference and lower spatial reuse ratio on the throughput is observed in the five hops scenario. This severe effect is due to the specific positions of the hidden and exposed terminals in the connected corridors. It is, however, observed that the throughput of the six hops is higher than that of the five hops due to its higher spatial reuse ratio and hence lower effect of the accumulative interference. Similarly the seven hops has higher throughput as compared to both six and five hops because of its further higher spatial reuse ratio. The higher spatial reuse ratios in the six and seven hops scenarios are attained due to the specific positions of the nodes in the corridors.

Figure 3 shows that ns-3 simulated results are matching with the results from the test-bed in the single hop scenario for fading parameter $m = 2.0$ while diverging in all other scenarios except for the six hops scenario. There the simulation results of all fading parameters m are almost identical with the test-bed results. Figure 4 shows that for the single hop scenario the ns-2 simulation results are almost identical with that of the test-bed for fading parameter $m = 2.0$. The figure shows that ns-2 simulated results in three and four hops scenarios are matching with the test-bed for various fading parameters m. Notably, simulations of ns-2 and ns-3 fail to reflect the higher spatial reuse ratio behavior of the six and seven hops than five hops like the test-bed.

The simulation results from both ns-2 and ns-3 show that none of the fading parameters m has a persistent match with the test-bed results in all multi-hop scenarios. We also observe that

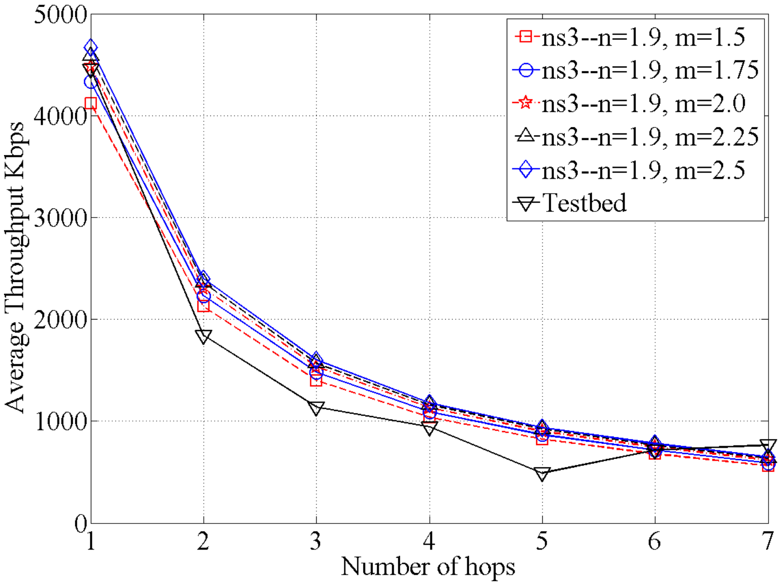


Figure 3: TCP throughput in experiment-1 versus ns-3 results for path loss exponent $n = 1.9$ *and different Nakagami parameters* m.

in contrast to ns-3, the ns-2 simulations have a closer match with the test-bed results except for six and seven hops cases, where ns-2 results are diverging from the test-bed larger than ns-3. It is observed as well that the throughput of a single hop TCP flow is higher in the test-bed than the simulated results for certain values of fading parameter m. This is due to wave-guiding signal propagation phenomena not correctly captured by the propagation models in the simulators. It is, therefore, hard to conclude which of the two simulators closer reflect the reality except for stating that both simulators give a rough match of the test-bed results.

5.2 Experiment-2: test-bed vs. simulations

In experiment-2, from the simulations of each simulator, we are getting five plots for the average throughputs (over all scenarios) for five Nakagami parameters. So for sake of simplicity of explanation and limitation of pages of the article, we present comparison of the results with a concise performance metric call throughput fairness index. We find that fairness index behaviours of both the simulators are quite different from the test-bed, which implies that average throughputs behaviours of simultaneous flows of simulations are also different from those of experiment-2 of the test-bed. The details of the throughput fairness index are given as follows.

In experiment-2 we compared the performance of the simulators with the test-bed using Jain fairness index f_s (5). The index takes values between 0 and 1. In (5) $X_i^{(s)}$ is the network's throughput share obtained by i^{th} flow and s is the number of simultaneous flows.

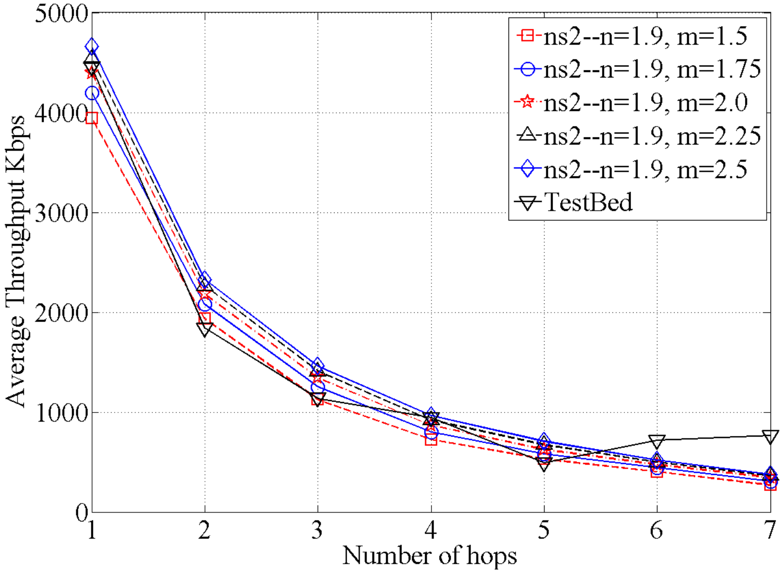


Figure 4: TCP throughput in experiment-1 versus ns-2 results for path loss exponent $n = 1.9$ and different Nakagami parameters m.

$$f_s = \frac{\left(\sum_{i=1}^{s} X_i^{(s)}\right)^2}{s \sum_{i=1}^{s} (X_i^{(s)})^2}. \tag{5}$$

In order to use the index in the case of flows with unequal characteristics we have to relate the actual measured throughput with a throughput share of the flow under ideal sharing condition [15]. Therefore, $X_i^{(s)}$ is computed as in (6). There $a_i^{(s)}$ is the actual throughput of the i^{th} flow measured in simulations and in the test-bed and $d_k^{(s)} = \frac{T_k}{s}$ is the throughput share under ideal sharing conditions over k hops. It is computed by dividing the throughput T_k of a single flow over k hops measured in experiment-1 by s.

$$X_i^{(s)} = \begin{cases} \frac{a_i^{(s)}}{d_k^{(s)}} & \text{if } a_i^{(s)} < d_k^{(s)} \\ 1 & \text{otherwise} \end{cases} \tag{6}$$

As we observe from Figure 5 and Figure 6 the fairness indexes obtained from the ns-2 and ns-3 simulators have opposite trends for different values of simultaneous flows and the number of hops. It is observed from ns-3 simulations in the Figure 5 that the fairness index is decreasing in scenarios one to four. The lowest fairness indexes are observed in scenarios five, six and seven for certain values of fading parameters m. Like in the test-bed, ns-3 simulations of scenarios five and greater show an increasing trends in the fairness indexes for different fading parameters. Clearly the fairness index obtained from ns-3 simulations is lower than the

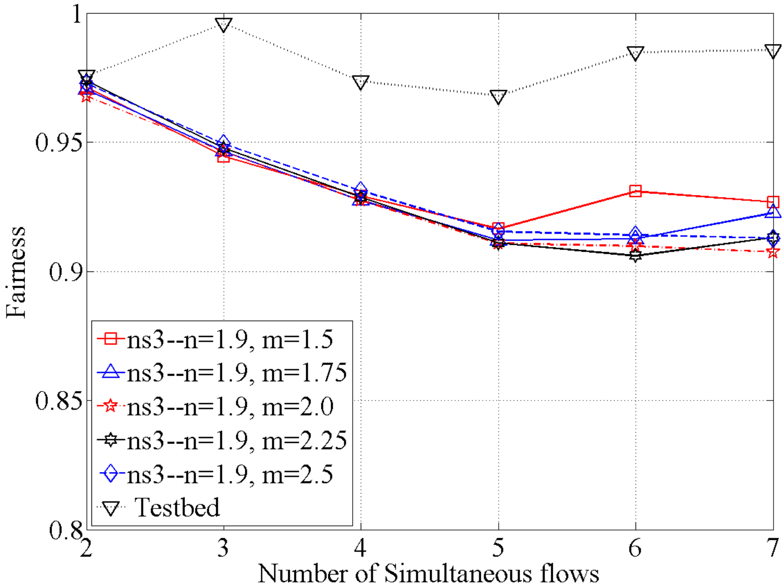


Figure 5: Jain fairness index in experiment-2 versus ns-3 results for path loss exponent $n = 1.9$ and different Nakagami parameters m.

one in the test-bed for all values of the fading parameters. It is however worth pointing out that the overall behavior of the index for Nakagami parameters $m = 1.5$ and $m = 1.75$ matches the index's behavior in the test-bed in scenarios three to seven.

Looking at the results from ns-2 simulations in Figure 6 we observe that the fairness indexes increase with increasing number of simultaneous flows and hops. In scenario three the fairness index in simulations matches exactly the values in the test-bed. Although the absolute values of the index obtained from ns-2 do not significantly deviate from the measured in the test-bed, however the overall development of the index is different from test-bed.

It is to be noted that wave-guiding propagation phenomena of radio waves in the test-bed are present in both single and simultaneous flow scenarios. However, in the simultaneous flow scenarios the probability of concurrent transmissions along the multi-hop path is higher than single flow scenarios. This results in higher value of the accumulative interference in experiment-2. We know that wave-guiding propagation phenomena of radio waves reduce the signal strength loss as compared to common radio waves propagation in space. So due to wave-guiding propagation, the accumulative interference has higher range to affect the desired reception of the signal along the multi-hop path. Hence the deviations of the simulations of simultaneous flow scenarios from test-bed are larger than single flow scenarios.

Overall, as in the case with experiment-1 none of the simulators was able to exactly reproduce the performance of the test-bed. Partially it depends on simulator specific implementation of protocols on MAC and (or) Transport layers. ns-2, for example, uses own implementation of TCP-Cubic congestion control. We however observe a better match of the network behav-

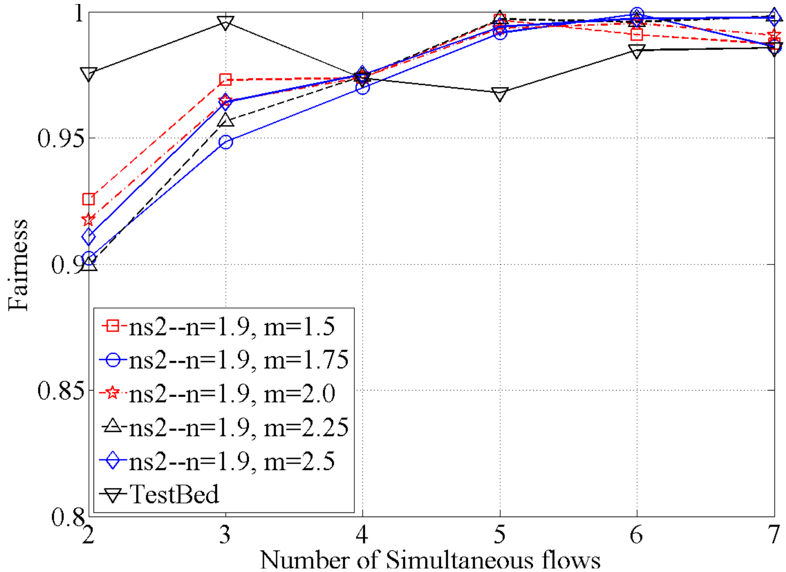


Figure 6: Jain fairness index in experiment-2 versus ns-2 results for path loss exponent $n = 1.9$ and different Nakagami parameters m.

ior produced by ns-3 simulator which uses native Linux implementation of TCP. The major problem in our opinion comes however from inability of the simulator's propagation models to capture all signal impairments mechanisms in the particular communication environment. The corridor environment of the test-bed exposes strong wave-guiding propagation phenomena, which places a great impact on the accumulative interference and the spatial reuse ratio.

6 Conclusion

This paper presents a comparative study between test-bed and simulations of the network simulators ns-2 and ns-3. The test-bed is multi-hop wireless network deployed in corridors in a non-linear chain topology, which challenges the commonly used empirical models of wireless propagation channel that are currently available in these simulators. The experiments done for this study include single and concurrent flows transmissions over a single multi-hop path. The goal is to explore how well these simulators reflect the reality represented by this test-bed carrying those flows.

Our simulations roughly match with test-bed results for single flow transmissions, which cause only limited accumulated interference and allow for good spatial reuse ratio of the network. Simulations deviate however more clearly from test-bed results for simultaneous flows transmissions. These transmissions increase the accumulative interference compared to single flow transmissions and thereby decreases the spatial reuse ratio of the network. In particular, for simultaneous flows transmissions simulations indicate considerably worse fairness between flows compared to test-bed results. This reveals that the wireless propagation channel models of the simulators are not correctly representing the wireless channel properties in the corridors, especially in scenarios involving accumulated interference in difficult environments such as corridors.

Deterministic wireless channel modeling for example based on ray tracing techniques can better capture reality into simulators, but require exact knowledge of location, shape, dielectric and conductive properties of all objects in the environments and it also requires extensive computational efforts for accuracy. This complexity motivates the use of empirical radio modeling although its shortcomings in correctly modeling complex environments. Our paper emphasizes the need for validation when using such modeling to study single channel multi-hop wireless network performance for more complex environments.

Future work include to extend this study by exploring how results match between simulations and real multi-hop wireless networks with linear chain topology for other indoor environments as well as outdoor environments. Thereby we can further characterize possible discrepancies important to be aware of when using simulations to predict performance in real networks.

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