Article

A New Linear Model for the Calculation of Routing Metrics in 802.11s using NS3 and RStudio

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Abstract: Wireless Mesh Networks (WMN) are a solution with a reasonable cost/benefit ratio when providing broadband internet access. The concept is being used not only in IEEE networks but also in other wireless networks such as cellular networks (4G/5G) and Low Power Wide Area Network (LPWAN). IEEE 802.11s is the facto standard and is well known for working with WMN. The standard defines Hybrid Wireless Mesh Protocol (HWMP) as a layer 2 routing protocol. The metric proposed by the protocol is Air Time Link (ALM), and the IEEE 802.11 standard proposes an equation for its calculation. This work proposes a new methodology for the calculation of ALM which has been developed in the following way: through several scripts, which simulate various WMN scenarios in NS-3, collect information in several databases, and then take the data to RStudio, where different statistical tests are developed, such as linear models (LM), generalized linear models (GLM), and other statistical tests for both the original and new model proposals.

The result is a new methodology for the calculation of metrics, using statistical techniques in the selection and validation of model regressors, presenting an a priori tool to improve the performance of the WMS's.

Keywords: WMN; 802.11s; HWMP; ALM; NS3; RStudio; LM; GLM

1. Introduction

WMNs have been designed to provide low-cost and high-performance connectivity solutions. This type of network allows communications between nodes without the need for an access point, without the need for what is known as "infrastructure mode". All WMNs nodes can act as repeaters and as clients at the same time. The concept of WMNs is based on multi-hop networks in order to cover large geographical areas. The simplicity in adding the new routers make WMNs as the preferred technology for applications viz., intrusion detection systems, remote video surveillance, smart grids, environmental monitoring. In many applications, WMNs are expected to support internet services to heterogeneous clients[1].

Fig. 1 depicts the need for supporting Multi-Radio functionality on Mesh Router. But multi radio feature may be enabled on mesh routers and gateways to obtain the best results out of WMNs[1].

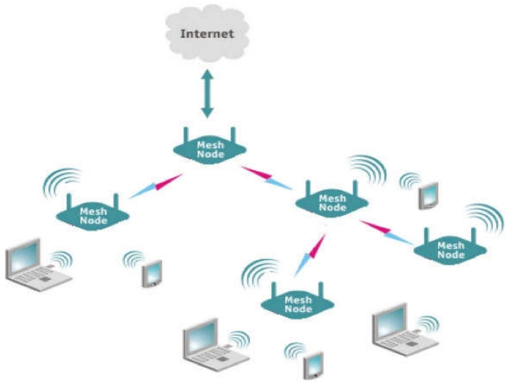

Figure 1. Multi-radio wireless mesh network [2].

HWMP is the layer 2 routing protocol with three clear objectives to form WMNs: node discovery and mesh establishment, metric calculation and route maintenance, and security and synchronization. [3, p. 11]

ALM metric computation comes from:

$$ALM = \frac{[O + \frac{Bt}{r}]}{(1-ef)} \quad (1)$$

Where:
O y Bt, standar IEEE 802.11s.
r, bit rate.
ef, frame error. [3, p. 11]

Routing metrics predict the cost of the route calculated by the routing protocols. They provide quantifiable values that can be used to judge the cost or efficiency of a route[4].

NS-3 is a discrete-event network simulator for Internet systems, targeted primarily for research and educational use. ns-3 is free, open-source software, licensed under the GNU GPLv2 license, and maintained by a worldwide community[5].

In NS-3, the development of the implementation of the different network protocols in several types of files, the most important are the .h files, which are the libraries, and the .cc files, which are the C++ language routines. Thus, the implementation of the IEEE 802.11s standard is defined by various of these file types and others.

R is a language and environment for statistical computing and graphics. It is a GNU project which is similar to the S language and environment which was developed at Bell Laboratories (formerly AT&T, now Lucent Technologies) by John Chambers and colleagues. R can be considered as a different implementation of S. There are some important differences, but much code written for S runs unaltered under R.

R provides a wide variety of statistical (linear and nonlinear modelling, classical statistical tests, time-series analysis, classification, clustering, …) and graphical techniques, and is highly extensible. The S language is often the vehicle of choice for research in statistical methodology, and R provides an Open Source route to participation in that activity[6].

RStudio is a free, open-source IDE (integrated development environment). Its interface is organized so that the user can clearly view graphs, data tables, R code, and output all at the same time[7].

The objective of this work is to provide a new tool for calculating the metrics for the wireless routing protocol based on HWMP and is divided as follows. Section II contains a compilation of previous works. Section III presents the design criteria of the proposal in the two used software Ns-3 and RStudio. Section IV describes the tests and cases that gave

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proper support to verify the correct functioning of the proposal. Finally, Section V presents the project main conclusions and possible future improvements.

2. Related Works

A lot of research has gone into understanding and evaluating the performance of WMNs with different scenarios.

In[8], a new metric for the HWMP Protocol is proposed based on two criteria: the diversity of the two-hop channel and the hop delay. This new metric called NMH has been tested, simulated, and compared with another WCETT metric using NS-2, obtaining the decrease in the end-to-end delay of the network and the increase in throughput.

In[9], a routing protocol based on a metric is suggested that takes different parameters, such as hop count, energy cost, and traffic load, the same ones used in a simple linear combination of the form:

$$cost = cost' + \sum \alpha_i \times metric_i \quad (2)$$

Simulation analysis shows that our approach outperforms single-metric routing protocols while supporting flexible service criteria, including load balancing at access points.

In[10], there is a proposal for an improvement to the HWMP metric, which considers the flow of traffic and allocates network resources efficiently. In addition, this method manages the quality of links both historically and in real-time to be more sensitive to variations in the quality of the links.

In[11], it is proposed to use ETX (Expected Transmission Count) as a metric for HWMP and compare it with HWMP based on hop count. To accomplish this goal, the study uses an NS-2, obtaining a decrease in delays but an increase in the overhead.

In[12], it considers a metric called ETX-3 hop, it includes a more exact method to obtain the quality of the link, and its name is because it takes three nodes to calculate the metric, demonstrating improvements in the throughput of the network concerning ETX.

Finally, in[13] the study proposes to apply the Analytic Hierarchy Process (AHP), to calculate the combination of two new metrics based on four QoS parameters: delay, bandwidth, security, and loss probability.

3. Proposed Solution

The present work proposes a new methodology to calculate the metrics of a routing protocol in WMNs, specifically the implementation of HWMP in NS-3.

The aforementioned methodology consists of, based on modifications in the NS-3 HWMP code, collecting data, not only from the current ALM metric but also from other network characteristics, for example, layer 4 protocol, number of packets, mesh size, and more. After this process, the data is saved in a compatible file and taken to RStudio with two purposes. First, statistically evaluate the initial model and second, propose improvements in the metric calculation.

3.1. Software & Hardware

The usage of NS-3 version 3.30 is required and runs on a Linux Ubuntu 20.04.5 LTS system with an Intel Core i5-5200 CPU @ 2.2GHz x 4, 8 GB RAM, x64 Architecture.

RStudio version 2022.07.1 +554 is used and runs on a Windows 11 PRO version 21H2 system with an Intel(R) Core(TM) i7-8565U CPU @ 1.80GHz-2.00 GHz, 8 GB RAM, x64 Architecture .

3.2. Testing and data collection in NS-3

To begin with, the process used the NS-3 network simulator to write several scripts. The first one is a modification to the airtime-metric.cc which in its original version allows us to obtain the ALM metric whereas the modification lets us obtain additional variables to protocol performance.

Then, the development of the mesh-ping.cc script was done on the original mesh.cc script, the objective is to create an *.xls* report of the metrics every second and not only at the end of the simulation, to evaluate network performance continuously.

Similarly, the mesh-tcp.cc script was developed with similar characteristics to the previous one, but with the TCP protocol in layer 4.

Lastly, the wifi-phy-header.cc script is modified to work with data packets that have an extension of up to 8192 Bytes since the original script only allows it up to 2048.

The next scripts: *peer-management-protocol.cc, peer-management-protocol_mac.cc, peer-link.cc, mesh-point-device.cc, mesh-wifi-interface-mac.cc, hwmp-protocol.cc, mesh-helper.cc* y *hwmp-protocol-mac.cc*; had a modification to present only the network performance information we need, for example, unicast and broadcast packets in transmission and reception.

The simulator has a configuration with the next parameters:

Table 1. Parameters of simulation

Parameters	Value
Protocol L4	UDP TCP
Step size	15 30 50
Mesh size	3 x 3 4 x 4 5 x 5
Packet size	1024 Bytes 2048 Bytes 4096 Bytes 8192 Bytes
Number of interfaces	1 2 3

The simulation was run for 2.5 seconds with all the possible interactions between the simulation parameters, simulation variables, and protocol performance variables. The test databases were generated and will be processed in RStudio.

Simulations generated two databases:

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Table 2. Databases

Archive	Observations	Numbers of variables	Variables
mesh.csv	101070	7	FAILAVG METRIC MXN L4 M_STEP M_PACKET INTERFACES
mesh_udp_2.csv	61007	10	FAILAVG TXDURATION METRIC MXN L4 M_STEP M_PACKET PDF COMP TXX

Next, variables explanation:

FAILAVG: ef, defined in standard IEEE 802.11s
TXDURATION: Bt/r, defined in standard IEEE 802.11s
METRIC: ALM metric, defined in standard IEEE 802.11s HWMP
MXN: Mesh size
L4: Layer 4 protocol
M_STEP: Distance between nodes
M_PACKET: Packet size
INTERFACES: Number of interfaces, for IEEE 802.11b channels 1, 6 y 11
COMP: Inverse complement to 1 de FAILAVG

$$COMP = \frac{1}{1-FAILAVG} \quad (3)$$

PDF: Packet Delivery Function, can be defined as the ratio of the number of data packets delivered to the total number of packets sent. This illustrates the efficiency of data delivered to the destination.

$$PDF = \frac{\sum Number\ of\ packets\ received}{\sum Number\ of\ packets\ sent} \quad (4)$$

Greater the value of packet delivery ratio means the better performance of the protocol[1].

TXX: Network performance
TXX is YES when PDF > 0.6
TXX is NO when PDF < 0.6

3.3. The calculation of ALM in RStudio

As mentioned above, I use RStudio for the statistical analysis of the databases obtained in NS-3.

For the statistical tests, the databases obtained in .xls format have been converted to a .csv format.

From here on, the simulation parameters, simulation variables and performance variables will be called linear model (LM) regressors.

The database I use for this first analysis is mesh.csv.

According to the IEEE 802.11s standard, the regressor that determines the ALM value is FAILAV and the rest of the terms in the equation are not important since they are constant.

The LM for the original model IEEE 802.11s is :

lmesh1 = lm (log (METRIC) ~ FAILAVG, data=mesh) (3)

Next, the modification of the original model takes place with an LM including all the regressors of the database and also incorporates the square and the cube of FAILAV:

lmesh2 = lm (log (METRIC) ~ FAILAVG + I(FAILAVG^2) + I(FAILAVG^3) + MXN + M_STEP + M_PACKET + INTERFACES + L4, data=mesh) (4)

Then, to determine the regressors that are significant for the model, I perform analysis of variance (ANOVA) and STEPWIZE selection tests. At this point regressors can be discarded.

The final step is the creation of an LM to use the COMP regressor, like this:

lmesh3 = lm (METRIC ~ COMP + I(COMP^2) + I(COMP^3) + MXN + M_STEP + M_PACKET + INTERFACES + L4, data=mesh) (5)

I perform ANOVA and STEPWIZE tests to the model, and for lmesh1, lemsh2 and lemsh3 I obtain the graphs of the residuals.

3.4. Proposed new model.

The current proposal has a new model using the general linear model (GLM), to better predict METRIC and taking into consideration that one of the results of working with LM in the previous section is that the data distribution is not Gaussian.

From this point on, I work with the mesh_udp_2.csv database, with the aim of obtaining a model that does NOT depend on the protocol in the L4 layer, so this regressor disappears from the LM.

glmesh1 = glm (formula = METRIC~FAILAVG + MXN + M_STEP + M_PACKET + INTERFACES + TXDURATION + PDF, family = poisson (link="log"), data = mesh_udp_2) (6)

For this glmesh1 use a distribution of POISSON and LOG as a link function.

3.5. Network performance

To model the performance of the TXX network, I use GLM's, for the reasons explained above and also because it is a categorical variable; in this model, TXX is the dependent variable, METRIC is the covariate, and the rest of the regressors are independent variables.

The proposed model is:

glmesh2 = glm (formula = TXX ~ METRIC + FAILAVG + MXN + M_STEP + M_PACKET + INTERFACES + TXDURATION, family = binomial (link="logit"), data=mesh3) (7)

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I use a distribution of BINOMIAL and LOGIT as the link function.

Next, I proceed to perform the Analysis of Covariance (ANCOVA) analysis which consists of three additional tests, which are called statistical assumptions.

1. Equality of variances: the null hypothesis is that the variance is equal, I use the LEVENE test.
2. Independence of the data: the null hypothesis is that the data are independent, I use the ANOVA test.
3. Homogeneity of the regression slopes: the null hypothesis is that there is the homogeneity of the regression slopes, I use the ANOVA test.

All the scripts as well as the databases can be reviewed in [14].

4. Results

The results are presented in the order in which the tests were performed with the most relevant tables and graphs. For more detailed results see [14].

4.1. The original model and its modifications.

A summary of the results of the statistical tests of lmesh1 and lmesh2 are in fig. 2. The obtained results used the STARGAZER function.

	Dependent variable:	
	log(METRIC)	
	(1)	(2)
FAILAVG	1.555***	1.238***
	(0.001)	(0.005)
I(FAILAVG2)		-0.708***
		(0.017)
I(FAILAVG3)		2.067***
		(0.016)
MXN		0.00003
		(0.00002)
M_STEP		-0.0001***
		(0.00001)
M_PACKET		0.00000***
		(0.00000)
INTERFACES		-0.0004**
		(0.0002)
L4UDP		0.001***
		(0.0003)
Constant	4.972***	5.003***
	(0.0003)	(0.001)
Observations	82,048	82,048
R2	0.951	0.988
Adjusted R2	0.951	0.988
Residual Std. Error	0.073	0.036
F Statistic	1,579,704.000***	836,808.400***
Note:	*p<0.1; **p<0.05; ***p<0.01	

Figure 2. STARGAZER lmesh1 & lmesh2.

It is visible that lmesh2 has an increase in the values of R2 and adjusted R2 and decreases the error by increasing the regressors; all this is concerning lmesh1, so it is capable of explaining a high percentage of the observed variability. The F test shows that it is significant. The conditions for this type of regression are satisfied.

Furthermore, the value of *Pr* in the ANOVA test tells us that the models lmesh1 and lmesh2 are not the same models.

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```
Analysis of Variance Table

Model 1: log(METRIC) ~ FAILAVG
Model 2: log(METRIC) ~ FAILAVG + I(FAILAVG^2) + I(FAILAVG^3) + MXN + M_STEP +
    M_PACKET + INTERFACES + L4
  Res.Df    RSS Df Sum of Sq     F    Pr(>F)
1  82046 442.26
2  82039 108.44  7    333.82 36077 < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

Figure 3. ANOVA lmesh1~lmesh2.

The STEPWISE backward test tells us that all the regressors remain in the model due to Akaike's an Information Criterion values (AIC).

```
Stepwise Model Path
Analysis of Deviance Table

Initial Model:
log(METRIC) ~ FAILAVG + I(FAILAVG^2) + I(FAILAVG^3) + MXN + M_STEP +
    M_PACKET + INTERFACES + L4

Final Model:
log(METRIC) ~ FAILAVG + I(FAILAVG^2) + I(FAILAVG^3) + MXN + M_STEP +
    M_PACKET + INTERFACES + L4


  Step Df Deviance Resid. Df Resid. Dev       AIC
1                      82039   108.4432 -543864.5
```

Figure 4. STEPWIZE Summary

In other words, the original IEEE 802.11s model improves with the inclusion of the FAILAVG square, cube, and additional regressors.

We perform an analysis of the residuals for lmesh1 that allows us to visualize that data distribution is not Gaussian since the pattern of the residuals is the same as the pattern of the data, so the model is not linear.

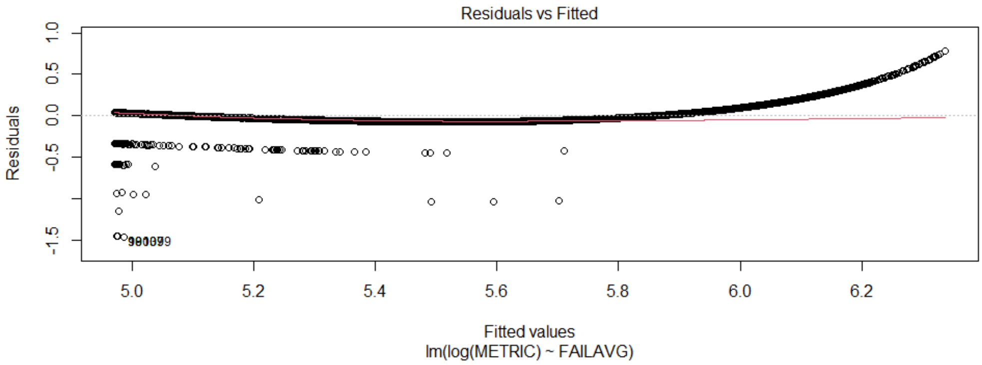

Figure 5. Residuals of lmesh1.

Ignoring for the moment the non-linearity of the data, I modify the original model in lmesh3 and to get the following results.

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```
Call:
lm(formula = METRIC ~ COMP + I(COMP^2) + I(COMP^3) + MXN + M_STEP +
    M_PACKET + INTERFACES + L4, data = mesh1)

Residuals:
     Min       1Q   Median       3Q      Max
-175.057   -0.021    0.213    0.471    1.207

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept) -1.355e+00  1.553e-01  -8.729  < 2e-16 ***
COMP         1.512e+02  1.878e-01 804.931  < 2e-16 ***
I(COMP^2)   -1.429e-01  6.859e-02  -2.084   0.0372 *
I(COMP^3)    1.037e-02  7.074e-03   1.466   0.1426
MXN          8.295e-03  2.561e-03   3.239   0.0012 **
M_STEP      -6.870e-03  1.327e-03  -5.178 2.25e-07 ***
M_PACKET     2.583e-05  5.454e-06   4.737 2.17e-06 ***
INTERFACES  -2.693e-02  1.988e-02  -1.354   0.1756
L4UDP        7.248e-02  2.977e-02   2.435   0.0149 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 4.13 on 82039 degrees of freedom
Multiple R-squared:  0.9981,    Adjusted R-squared:  0.9981
F-statistic: 5.323e+06 on 8 and 82039 DF,  p-value: < 2.2e-16
```

Figure 6. lmesh3 Summary.

For lmesh3 we plot the residuals and although we manage to fit the residuals to a Gaussian distribution, the model has too many regressors that are not significant.

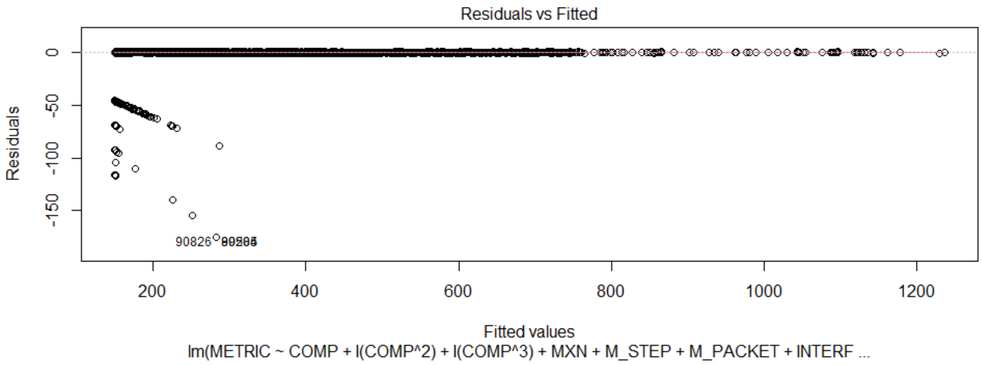

Figure 7. Residuals of lmesh3.

Computing a new regressor COMP, as the inverse for the complement to 1 from the error, allows us to have a model with a GAUSSIAN distribution. It better fits an LM, where the chosen regressors contribute in a more significant way to the calculation of the metric. However, this happens in a very marginal way since the increase in R2 and adjusted R2 is very low.

4.2. The proposed model

The proposed glmesh1 model presents the upcoming summary and residuals graph.

```
Call:
glm(formula = METRIC ~ ï..FAILAVG + MXN + M_STEP + M_PACKET +
    INTERFACES + TXDURATION + PDF, family = poisson(link = "log"),
    data = mesh_fit)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.0604  -0.7266   0.2707   0.4814  12.3969

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept)  3.938e+00  1.696e-01  23.221  < 2e-16 ***
ï..FAILAVG   1.642e+00  8.492e-03 193.410  < 2e-16 ***
MXN         -7.876e-04  3.835e-04  -2.054  0.03998 *
M_STEP       1.771e-04  1.950e-04   0.908  0.36385
M_PACKET    -4.445e-07  7.545e-07  -0.589  0.55578
INTERFACES  -4.589e-03  2.746e-03  -1.671  0.09464 .
TXDURATION   7.352e-04  1.165e-04   6.310 2.79e-10 ***
PDF         -1.633e-02  5.848e-03  -2.793  0.00523 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 38539.8  on 1280  degrees of freedom
Residual deviance:  1588.7  on 1273  degrees of freedom
AIC: 10636

Number of Fisher Scoring iterations: 4
```

Figure 8. glmesh1 Summary.

As shown, the non-significant regressors of the model are without a doubt M-STEP, M-PACKET, and working with INTERFACES allows a chance to improve their significance. In addition, the high value of AIC is a factor to take into account.

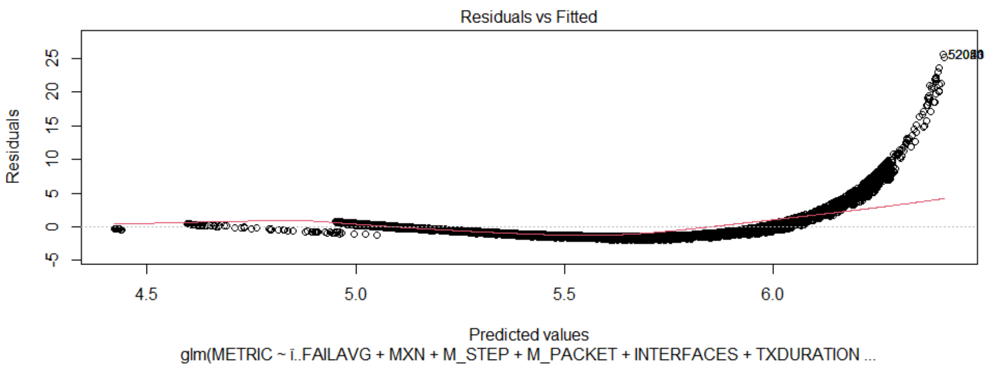

Figure 9. Residuals of glmesh1.

The residual analysis indicates that the data better fit the proposed Poisson distribution, observing several outliers or influential values. This is basically due to the number of samples in the database and could be a possible anomaly of the Big Data warned at the end of the document.

4.3. Proposal for network performance

Results for glmesh2 are:

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```
Call:
glm(formula = TXX ~ METRIC + MXN + M_STEP + M_PACKET, family = binomial(link = "logit"),
    data = mesh_fit)

Deviance Residuals:
    Min       1Q   Median       3Q      Max
-2.2557  -0.6895   0.3375   0.7499   1.8453

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept)  8.092e+00  4.957e-01  16.327  < 2e-16 ***
METRIC      -4.506e-03  8.146e-04  -5.532 3.16e-08 ***
MXN         -1.795e-01  1.460e-02 -12.291  < 2e-16 ***
M_STEP      -5.847e-02  7.357e-03  -7.948 1.89e-15 ***
M_PACKET    -4.057e-04  2.872e-05 -14.126  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for binomial family taken to be 1)

    Null deviance: 1703.5  on 1280  degrees of freedom
Residual deviance: 1201.5  on 1276  degrees of freedom
AIC: 1211.5

Number of Fisher Scoring iterations: 5
```

Figure 10. glmesh2 Summary.

As shown, all the regressors are significant for the model with an acceptable AIC, which indicates that the choice of glmesh2 to model the network performance, based on METRIC as a covariate, is adequate.

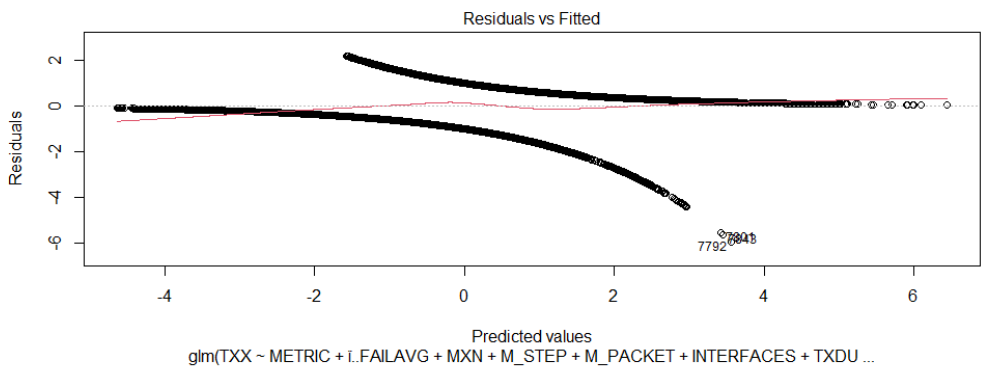

Figure 11. Residuals of glmesh2.

The ANCOVA analysis results performed on glmesh2 are summarized in table 3. This analysis allows us to have a decision tool on the regressors that meet the 3 statistical assumptions used to work with GLM's.

Table 3. Statistical tests.

Regressor	Test 1	Test 2	Test 3
MXN	YES	YES	YES
FAILAVG	YES	YES	YES
M_STEP	YES	YES	NO
INTERFACES	YES	YES	YES
M_PACKET	YES	NO	NO

5. Conclusions

In this work I propose a new methodology for the calculation of metrics, starting from simulations in NS-3, to then process the databases in Rstudio. I use statistical techniques such as LM, GLM, ANOVA, ANCOVA, STEWIZE, for the election and validation of model regressors, presenting an a priori tool to define, eliminate or enhance network variables, in the calculation of metrics in WMS's protocol.

In the same way, I present a new model based on GLM to predict the performance of the WMN's, as a previous process to take the new model to the simulator and later to real scenarios.

6. Future studies

For future findings, it is crucial to consider the computational cost derived from this work, that is, how the inclusion of new regressors and new calculation forms affects the data processing in mobile devices. This problem has to be addressed, for example, by using the Taylor series to simplify the calculation of metrics and relieving processing tasks in network devices, to finally evaluate the computational cost compared to traditional options.

Future studies can work on the incorporation of new metrics in the proposed models, metrics explained in works such as[4] [15], .

It is relevant to continue the research by taking the proposed models to the simulator for a first evaluation and, if necessary, continue with their implementation in real scenarios.

As noted in one of the work sections, it is possible to experiment by reducing the number of samples to values close to 1000 to avoid certain Big Data anomalies.

Supplementary Materials: The following supporting information can be downloaded at: https://github.com/jgochoa/Mathematical-model-for-the-choice-of-metrics-in-the-IEEE-802.11s-HWMP.

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