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QUALITY OF SERVICE IN WI-FI NETWORKS COEXISTING WITH LTE NETWORKS IN UNLICENSED BAND

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ABSTRACT

This paper evaluates the coexistence of LTE and Wi-Fi networks in 5 GHz non-licensed bands. It proposes a model of quality-of-service degradation index on Wi-Fi to measure the performance and latency network. First, Wi-Fi and LTE in 5 GHz non-licensed bands and the carrier aggregation technique are introduced. Then, it discusses the LTE-U and LTE LAA deployment scenarios and the coexistence evaluation model. Further, it provides an indoor coexistence simulation scenario following the recommendations of the 3GPP-TR089 for UDP and TCP FTP transmissions with LTE LAA. This paper is concluded by the Wi-Fi operator's degradation of performance, and network latency was found during its coexistence with the LTE operator.

Keywords: *Wi-Fi, LTE, Throughput, Coexistence, Latency.*

1. INTRODUCTION

Currently, the LTE transmission initiatives in the unlicensed 5 GHz band are still a matter of discussion. They could involve increasing capacity for LTE mobile operators of almost 500 MHz. However, also, they could mean a potential degradation in the performance of technologies that operate without a license, even though Wi-Fi is a technology with at least 15 years in the market, continues to grow.

The increase in mobile data traffic and the number of devices worldwide is a subject of study by mobile operators due to the possible shortage of the spectrum. In 2006 alone, nearly half a billion mobile devices were added, reaching almost eight billion worldwide; thus, thirty times more traffic was generated per month worldwide than last year [1], [2]. In the face of a potential spectrum shortage, some operators and manufacturers of LTE solutions, a wireless technology defined by the 3Gpp international agency, have led coexistence initiatives to transmit LTE over the 5 GHz unlicensed band. By using the coexistence, mobile operators intend to use almost 500 MHz available in the 5 GHz band, a band that has been used by Wi-Fi networks for more than 15 years [1], [3]. Certainly, Wi-Fi networks have been the basis for different massive access strategies for governments worldwide, including Colombia, with the "Free Wi-Fi Zones for People" project of the Ministry of Information Technologies and Communications [4].

Nowadays, it is required to increase the unlicensed spectrum use capacity. Alternative technologies to Wi-Fi have been presented as Licensed Assisted Access (LAA) and the second called LTE Unlicensed (LTE-U) as a first approach to increase the capacity of mobile operators. However, these proposals have generated concern in the entities that regulate the use of the electromagnetic spectrum for the possible impact of this technology's coexistence with native communications in the unlicensed band, precisely Wi-Fi.

According to the above, it is required to analyze the impact on the Quality of Service (QoS) in Wi-Fi networks coexisting with LTE networks. This paper shows in detail a series of simulations of this coexistence, considering possible parameters or metrics to evaluate the performance and, in general, the impact of coexistence of these technologies in the same environment.

Currently, Wi-Fi networks have had such a degree of massification that almost all smart devices have Wi-Fi connectivity at least [1]. It means that any possible degradation over Wi-Fi networks must be analyzed to evaluate its impact and, this way, take the relevant measures of regulation and control. The present article evaluates Wi-Fi network performance in coexistence with LTE in the non-licensed band through the degradation index and network latency performance. The paper is organized as follows: Section 2 presents the methodology proposed and a brief introduction to Wi-Fi and LTE in non-licensed bands. Section 3 presents the model used in the simulation to determine the degradation rate of the network under coexistence; subsequently, it describes the simulation's configuration and discusses the results obtained. Finally, section 4 presents the conclusions about the main ideas of this research.

2. METHODOLOGY

In order to propose a model to evaluate the coexistence of Wi-Fi and LTE in the non-licensed band [5], first, it is necessary to understand the existing technologies and then develop a coexistence evaluation model considering the degradation rate for latency and throughput over a Wi-Fi network.

2.1 Background Technology

2.1.1 Wi-Fi technology

Wi-Fi is a registered trademark of the Wi-Fi Alliance [6] and represents the wireless technology operating in the non-licensed ISM (Industrial, Scientific, and Medical) bands of 2.4 and 5 GHz under the IEEE 802.11 a/b/g/n/ac standards. Wi-Fi has been located in physical and data link layers of the OSI [6], [7].

Table 1 summarizes 802.11 standards that have been massified in the market as of December 2016 [1].

Table 1.Most Popular 802.11 Standards As December 2016. [1]

Feature	802.11n	802.11ac Wave 1	802.11ac Wave 2
Band	2.4 & 5 GHz	5 GHz	5 GHz
MIMO	Single User (SU)	Single User (SU)	Multi User (MU)
Data rate	300 - 450 Mbps	867 Mbps - 1300 Mbps	2.34 Gbps – 3.47 Gbps
Bandwidth	20 o 40 MHz	20, 40, 80 MHz	20, 40, 60, 160 MHz
Modulation	64 QAM	256 QAM	256 QAM
Special plots	2 - 3	2 – 3	2 – 4

2.1.2 LTE in non-license band technology

In order to have LTE over non-licensed band without affecting Wi-Fi networks guaranteeing the coexistence of these technologies, three large collaboration groups have been formed to specify coexistence mechanism: LTE-U Forum, 3GPP for LAA, and Multefire [8], [9].

✓ **LTE-U forum**

The industry partner forum defines the specifications for LTE-U (LTE-Unlicensed) based on the R12 of the 3GPP and focuses on specific markets.

✓ **3GPP**

The 3GPP defines global standardization for cellular network technologies such as LTE, including LWA (LTE – Wi-Fi Aggregation) and LAA (LTE License Assisted Access) R13.

✓ **Multefire alliance:**

This international association, formed in 2015, develops technical and product specifications for Multefire and standards based on 3GPP.

2.1.3 LTE-U

LTE in a non-licensed band (LTE-U) [9], [10] is focused on specific markets such as the United States, Korea, and India. LTE-U is perhaps the first mechanism that was proposed for coexistence [8], [10] incorporating:

1. Supplemental downlink (SDL) to improve download or downlink [11], [10].
2. Dynamic channel selection to avoid collisions with Wi-Fi using adaptive transmission techniques by carrier detection (CSAT) [12], [13].

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3. Migration support to LTE with access by assisted license LAA [14].

CSAT uses a time division transmission (TDM) pattern over an LTE-U secondary cell (SCell) with a time cycle called TCSAT [15], [16]. This TDM pattern is driven based on measured transmissions from Wi-Fi access points (APs).

The CSAT technique takes advantage of the MAC signaling given by the LTE carrier aggregation.

The Wi-Fi medium usage measurement takes place during the OFF time of the SCell LTE-U cell, designed to adjust the ON/OFF duty cycle.

An example of CSAT adaptive times is shown in figure 1. In the figure, the CSAT technique described by manufacturer Qualcomm, the ON time is modified considering the quantity of ON Wi-Fi AP in the environment. In CSAT, the LTE cell scans the medium for a period of time, and according to the observed activity, the algorithm reduces the LTE activity proportionally.

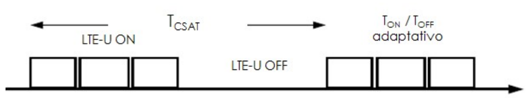

Figure 1.Qualcomm´s CSAT Description. [17]

The typical cycle length is 80 and 60 ms (include ON + OFF). For instance: 40/40 and 80/80. CSAT cycle length over the primary Wi-Fi channel is usually lower, enabling connection beacon transmission. Usually, CSAT cycles are constant, but they could change whether the LTE-U involvement was reduced, which is sometimes necessary to adapt to latency-sensitive applications.

Unlike the Wi-Fi's medium access given by carrier detection with collision avoidance (CSMA/CA), LTE-U uses CSAT and OSDL to access the medium and determine the LTE transmission opportunity.

2.1.4 LTE LAA

LAA refers to assisted access given by licensing, defined in the R13 of the 3GPP. Its deployment was focused in Europe and Japan on those regions with specific access procedures with Listen-Before-Talk (LBT) containment mechanisms [3], [18]. This feature has increased the attention of more countries compared with the LTE-U. As LTE-U does, it has the objective of LTE transmission in 5 GHz Wi-Fi bands [8].

Figure 2 summarizes the LAA technique. This technique performs channel aggregation between LTE in a non-licensed 5 GHz band and LTE in a licensed band which frequencies change between 400 MHz and 3.8 GHz depending on the country.

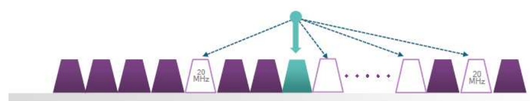

Figure 2. LAA Technique [8]

LTE in the non-licensed band works only in the downlink. It means that it only transmits in moments when there is no active Wi-Fi transmission, as is shown in figure 3.

Figure 3. LAA And Wi-Fi Transmission Coexistence. [8], [17]

The figure above shows the access technique "Listen Before Talking" or LBT, which was standardized in 2015 under the ETSI EN 301 893 [3], [6], [19] with the following considerations:

1. Energy Detect Threshold – it is the typical threshold for all carrier detection technologies.
2. Clear Channel Assessment – if no signal was detected according to the EDT, it starts the transmission.
3. Extended CCA – if the channel is busy (CCA), it waits for it to be clean, and once it happens, it starts waiting for a random number of additional CCA that indicate that the channel has remained clean before starting the transmission.

The coexistence analysis is made taking into account in-house deployments, as observed in figure 4.

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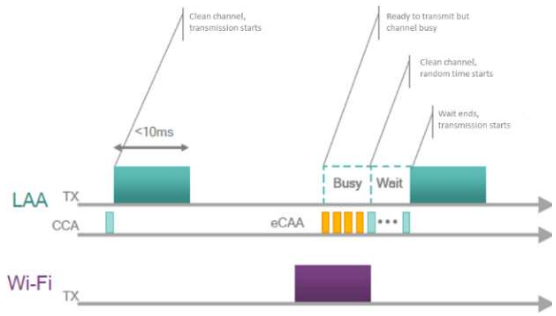

Figure 4. Medium Access In LAA. [12]

Next, based on the technologies explained above, the following model to evaluate the coexistence of Wi-Fi and LTE in the non-licensed band is proposed.

2.2 Coexistence Evaluation Model Proposed

The coexistence evaluation model proposes to assess the degradation rate for latency and network performance over a Wi-Fi network. The evaluation scenario for LTE in the non-licensed band and Wi-Fi coexistence is shown in figure 5a as the simulation framework of the system. From the previous scenario, the performance evaluation model considering a Wi-Fi network in coexistence with LTE and the interaction between input and output variables are defined, as shown in figure 5b.

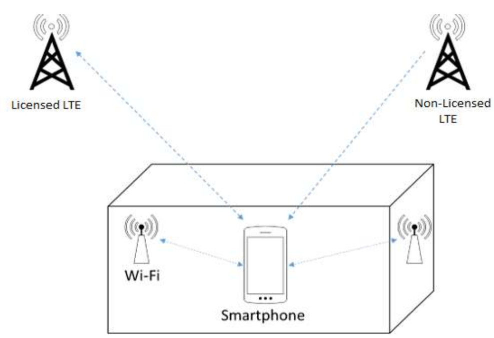

Figure 5.a. Evaluation Scenario For LTE in Non-Licensed Band And Wi-Fi Coexistence

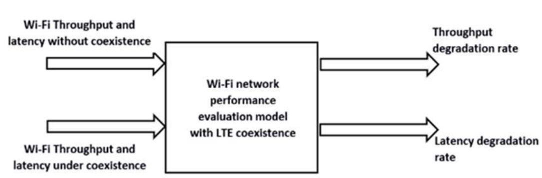

Figure 5.b. Performance Evaluation Model Considering A Wi-Fi Network In Coexistence With LTE

2.2.1 Input variables

The input variables to consider are only Throughput and Latency since the other QoS variables, such as signal strength and bit error, directly affect the throughput and latency parameters of the network [20].

1. Wi-Fi throughput and latency without LTE coexistence: Throughput and latency values are measured in the Wi-Fi interface when there is not LTE LAA transmission (LTE OFF).

2. Wi-Fi throughput and latency with LTE coexistence: Throughput and latency values are measured in the Wi-Fi interface when there is active transmission of the LTE LAA (LTE ON).

Other inherent interferences of the LTE transmission over unlicensed band are not considered for the above values.

2.2.2 Output variables

Like output variables, it has the latency and throughput network degradation index for Wi-Fi and LTE in non-licensed coexistence.

2.2.3 Relationship between input and output variables of the model

The relationship between the input and output variables of the model must be defined to obtain a unique dimensionless value for both latency and throughput.

The dimensionless output variable allows quantitative evaluation of the Wi-Fi network's performance based on network throughput and latency. This variable depends on the results obtained from the LTE LAA transmission in non-licensed 5 GHz band for downlink (LTE station to smartphone) as defined in Release 13 of the 3GPP without carrier aggregation.

2.2.4 Degradation index

The degradation index is a dimensionless real number, as defined in (1), which shows the development for throughput (TP) £T. A similar expression could be defined for latency (L) £L

$$\begin{array}{c} TP\ Wi-Fi \\ Degradation\ index \end{array} = \frac{TP\ WiFi_{with\ coexistence}}{TP\ WiFi_{without\ coexistence}} \quad (1)$$

The value defined in (1) is only valid when the Wi-Fi throughput without coexistence is different from zero.

- Let £T be the Quality of Service (QoS) degradation index for Wi-Fi in coexistence with LTE in the non-licensed band defined in (2).

- Let TP_W be the throughput value obtained in Wi-Fi when there is not LTE LAA transmission.

- Let TP_{WC} be the throughput value obtained in Wi-Fi when co-channel active transmission with LTE LAA.

Then,

$$£_T = \frac{TP_{WC}}{TP_W} \; ; for\, TP_w \neq 0 \quad (2)$$

In addition, it is necessary to review different situations that could arise to define exceptions:

- $£_T = 0$ occurs when TP Wi-Fi is null in co-existence.

- $£_T = 1$ occurs when there is no degradation of the Wi-Fi throughput in a coexistence situation with LAA, the throughput is maintained.

- $0 < £_T < 1$ occurs when the Wi-Fi throughput in coexistence condition is smaller than without coexistence; that is, it is considered a negative degradation in the performance of the Wi-Fi network.

- $£_T > 1$ occurs when the Wi-Fi throughput in coexistence is greater than when both operators are Wi-Fi, meaning that coexistence is convenient.

- $£_T = \infty$ is the degradation index when the TP Wi-Fi is null without coexistence; however, this condition does not allow to know the degradation level; therefore, it is considered an exception.

Once these exceptions have been reviewed, it defines the degradation model for the Quality of Service, as presented in (3):

$$£_T = \begin{cases} \frac{TP_{WC}}{TP_W} & when\ TP_W \neq 0 \\ 1 & when\ TP_{WC} = TP_W \\ Undefined & when\ TP_W = 0 \end{cases} \quad (3)$$

Based on the above expression, the results of the index will be interpreted as follows:

- $£_T > 1$, coexistence improves the performance of the Wi-Fi network.

- $0 < £_T < 1$, coexistence degrades the performance of the Wi-Fi network.

- $£_T = 1$, coexistence does not improve or degrades the performance of the Wi-Fi network.

The $£_T$ index allows evaluating if there is degradation in the performance of the Wi-Fi network under coexistence with non-licensed band LTE networks. In case of significant degradation, the index $£_T$ will have a value well above one. An ideal result would be $£_T = 1$ or less than one.

Since there are input variables for throughput and latency, two indicators are necessary for $£_T$ and $£_L$ performance evaluation as described in (3) and (4):

$$£_L = \begin{cases} \frac{\boldsymbol{L_{WC}}}{\boldsymbol{L_W}} & \boldsymbol{when\ L_W \neq 0} \\ \boldsymbol{1} & \boldsymbol{when\ L_{WC} = L_W} \\ \boldsymbol{Undefined} & \boldsymbol{when\ L_W = 0} \end{cases} \quad (4)$$

3. RESULTS

The simulation of coexistence conducted contemplates the recommendations of the 3GPP. It has been objective to reproduce the Wi-Fi and LTE in non-licensed band coexistence indoor scenarios, evaluating the performance impact on the Wi-Fi network using the simulation tool NS3 [19].

3.1 Simulation Scenario

The scenario simulation is indoors and has been specified by the TR.36.889 recommendation of the 3GPP. Table 2 shows the traffic models implemented in NS3 (using the LTE LAA coexistence library) [21].

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Table 2.Wi-Fi And LAA Traffic Models Implemented By NS-3 According To 3GPP Recommendation [20]

Traffic model	Wi-Fi Model	LAA Model
Model 1 FTP Files transfer according to a Poisson arrivals process *Lambda* arrival rate between 0.5 and 2.5 Size file: 0.5 MB	802.11n MIMO 2x2 20 MHz Maximum Data Rate MCS15 Channel model D Preamble detection -88 dBm CCA ED Wi-Fi to LAA signals -62 dBm DCF (Distributed coordination function) Beam-forming non-supported	20 MHz Exponential Backoff according to category 4 LAA ED in -72 dBm (default) LAA CCA slot time 9 us CWmin = 15, CWmax = 63 LTE LAA ON (TXOP = 8 ms) default

For the coexistence simulation, followed what is suggested by 3GPP considering two operators, A and B (BS A and BS B), with a 20 MHz channel. Then, coexistence is evaluated in two steps: in step one, both operators deploy Wi-Fi technology. Next, in step two, operator A changes and deploys LAA. In both cases, it simulated FTP transmission by UDP and TCP. As described above, it used an indoors deployment scenario as recommended by the 3GPP RAN1.

Figure 6 shows the simulation scenario with both operators, Base Station A and B, and User End A and B.

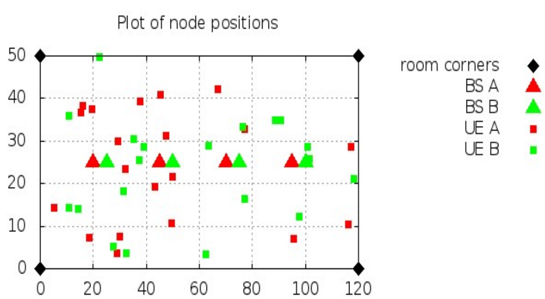

Figure 6. NS – 3 Simulation Scenario. [20]

Table 3 presents the variables considered in the simulation. The arrival rate of user packets is modeled with the Poisson distribution, four different values of ED levels, lambda, and LTE-ON time.

Table 3.Variables Used In Coexistence Simulation

Variables for Simulation	Value
Energy Detection threshold (ED)	-62, -72, -82, -90 dBm
Lambda (λ)	0.5, 1.5, 2.5, 3.5
Operational time or LTE-ON (TXOP)	4, 8, 16, 20 ms

3.2 Results of Coexistence Simulation

Figures 7 to 18 show the simulation results organized by energy detection threshold, lambda variation and LTE operation time when operator A transmits in LAA and operator B in Wi-Fi.

There are three scenarios:

- In the first one, lambda variation was made,
- In the second one, the threshold was varied,
- In the third, the TXOP was changed.

3.2.1 Lambda variation simulation

The lambda variation simulation was developed, setting TXOP at 8 ms and ED LAA at -72 dBm, while λ varied from 0.5 to 2.5. The Cumulative Distribution Function CDF was evaluated for FTP-UDP throughput, FTP-TCP throughput, FTP-UDP latency, and FTP-TCP latency, as shown in figures 7 to 10.

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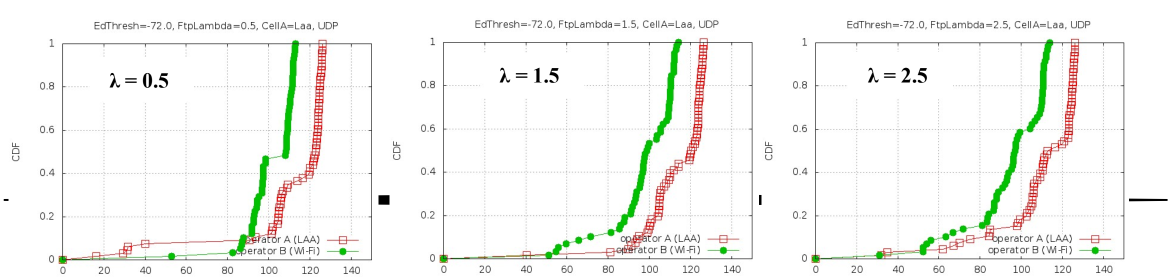

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Figure 7. CDF For FTP-UDP Throughput Including Different Values Of Lambda

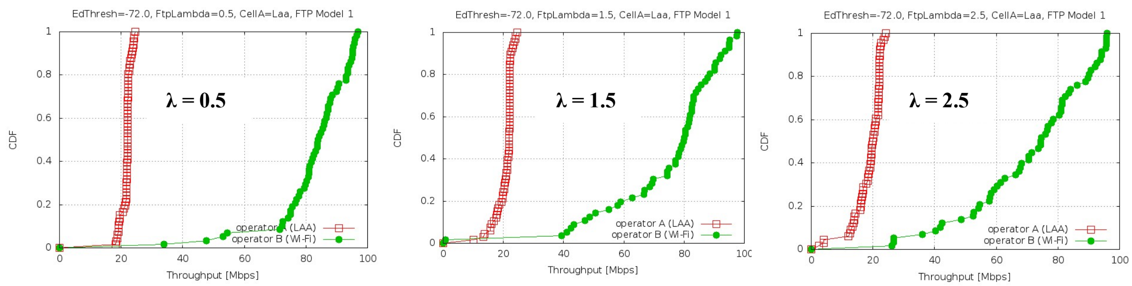

Figure 8.CDF For FTP-TCP Throughput Including Different Values Of Lambda

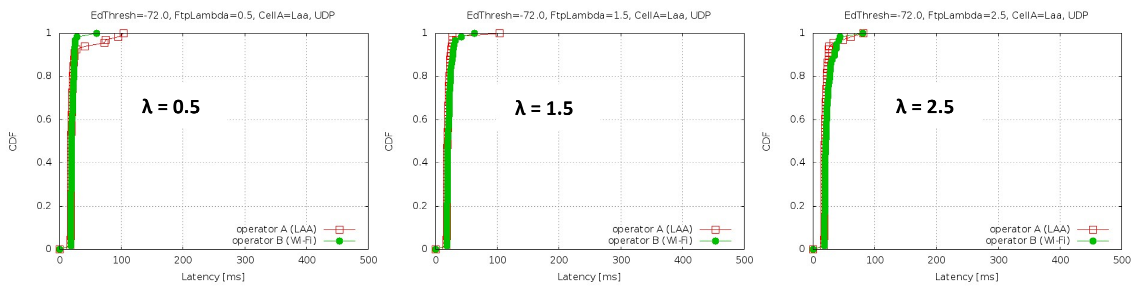

Figure 9. CDF for FTP-UDP latency including different values of lambda

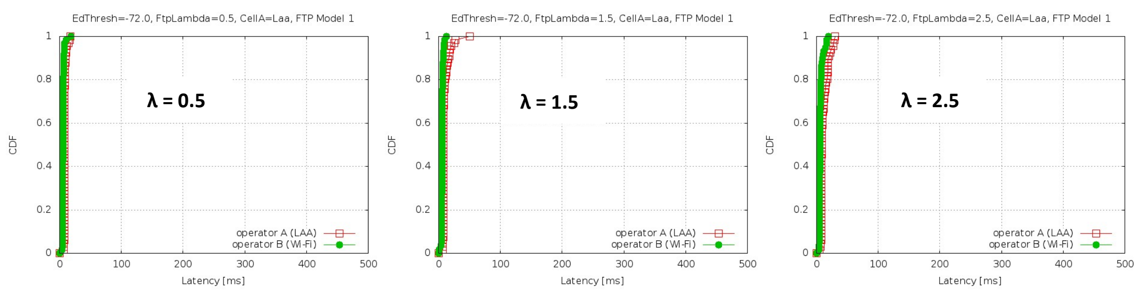

Figure 10. CDF for FTP-TCP latency including different values of lambda

Based on the information gathered by the simulation, it can be highlighted that the TCP contention window affects Wi-Fi throughput due to coexistence, which is more remarkable as the packet arrival rate λ increases, as shown above in the figures. On the other hand, the constant value of latency confirms its dependence on the threshold level, being a sensitive parameter that affects the coexistence indicator.

3.2.2 Threshold variation simulation

The threshold variation simulation was developed, setting TXOP at 8 ms and λ at 1.5, while ED varied from -62 to -82 dBm. The Cumulative Distribution Function CDF was evaluated for FTP-UDP throughput, FTP-TCP throughput, FTP-UDP latency, and FTP-TCP latency, as shown in figures 11 to 14.

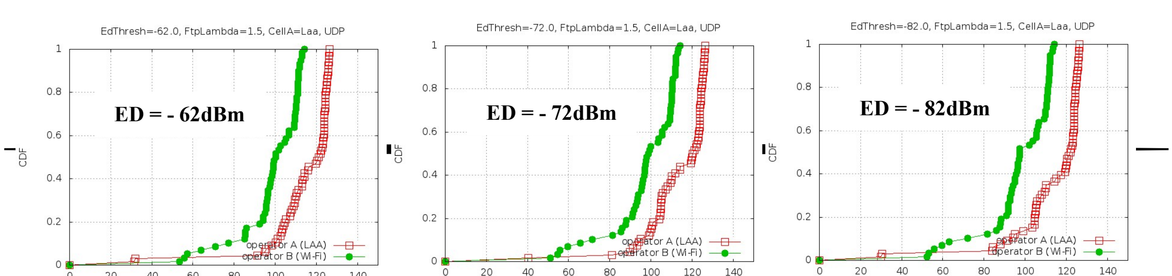

Figure 11. CDF For FTP-UDP Throughput Including Different Values Of ED

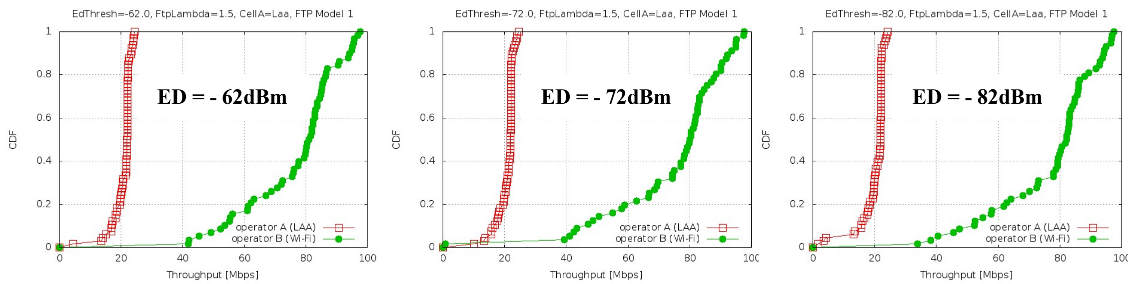

Figure 12. CDF For FTP-TCP Throughput Including Different Values Of ED

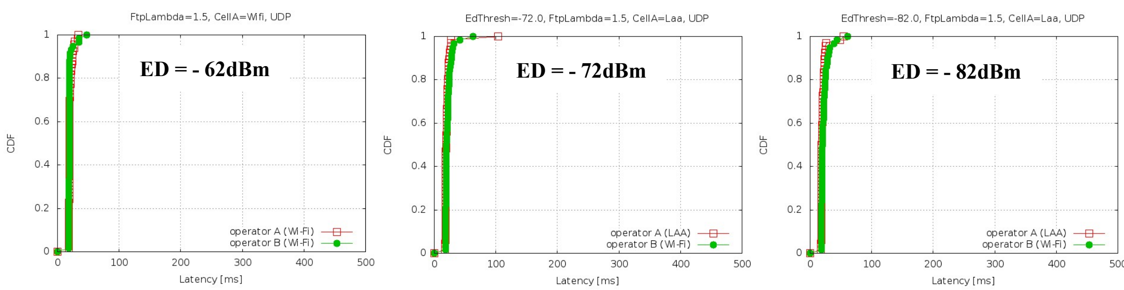

Figure 13. CDF For FTP-UDP Latency Including Different Values Of ED

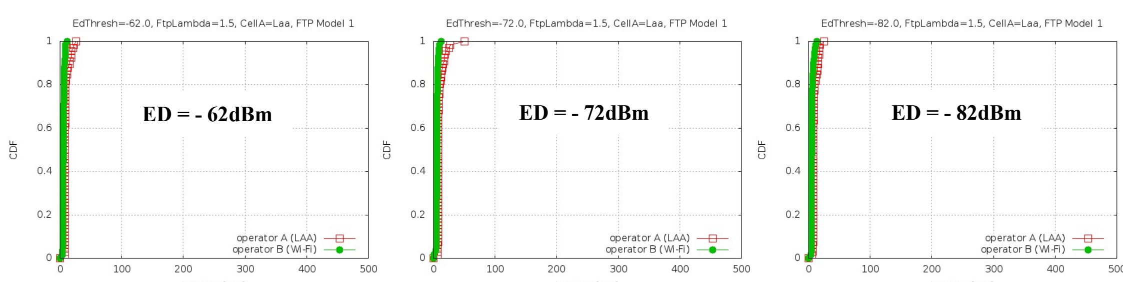

Figure 14. CDF For FTP-TCP Latency Including Different Values Of ED

The above simulations show that increasing the ED detection threshold affects latency for both UDP and TCP; an ED threshold of -62 dBm significantly affects network latency.

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3.2.3 TXOP variation simulation

The TXOP variation simulation was developed, setting ED LAA at -72 dBm and λ at 1.5, while TXOP varied from 4 to 16 ms. The Cumulative Distribution Function CDF was evaluated for FTP-UDP throughput, FTP-TCP throughput, FTP-UDP latency, and FTP-TCP latency, as shown in figures 15 to 18.

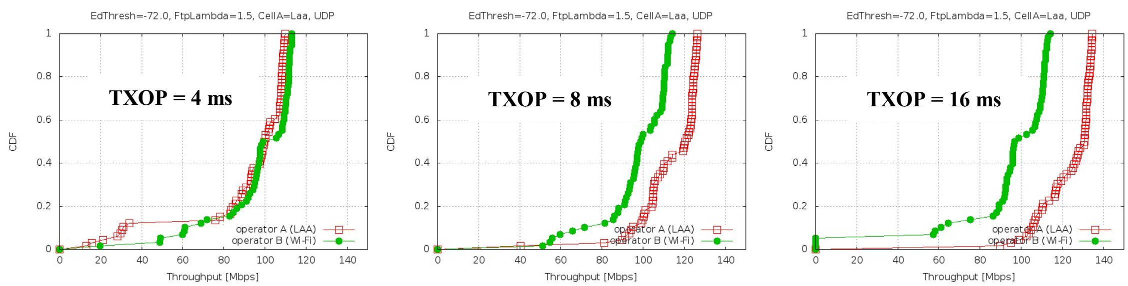

Figure 15. CDF For FTP-UDP Throughput Including Different Values Of TXOP

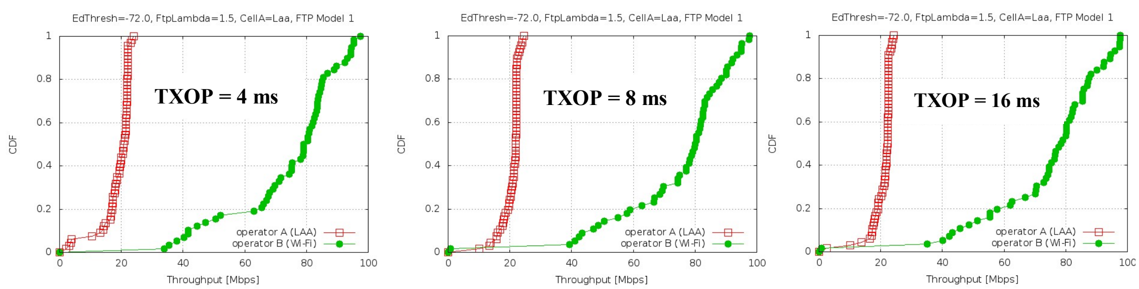

Figure 16. CDF For FTP-TCP Throughput Including Different Values Of TXOP

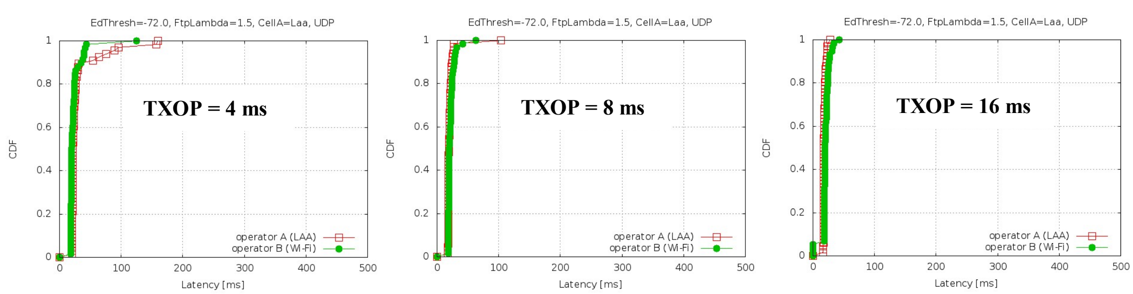

Figure 17. CDF For FTP-UDP Latency Including Different Values Of TXOP

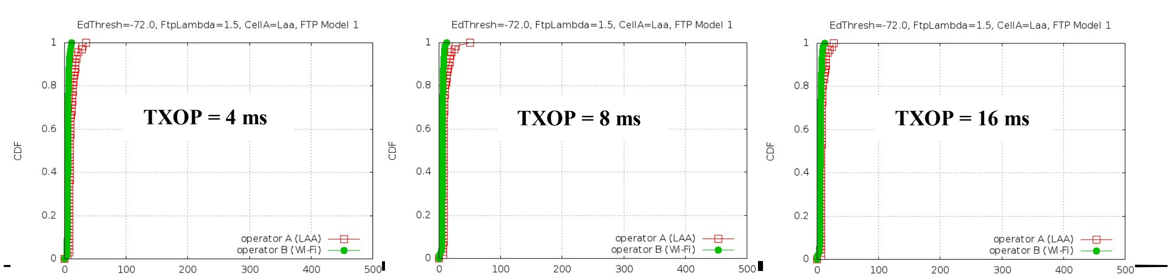

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Figure 18. CDF For FTP-TCP Latency Including Different Values Of TXOP

For this research, default values kept containment windows specified in LAA. As it can be seen above in the figures, the Wi-Fi network throughput in coexistence with LTE is sensitive to the transmission time of LTE (TXOP).

In general, the results shown above present negligible variation when both operators transmit in Wi-Fi and LAA. However, latency remains constant below 10 ms for FTP-TCP scenarios.

3.3 Results of Degradation Analysis

The analysis of results was made based on the degradation index £T for throughput and £L for latency. Figures 19 and 20 exhibit the throughput and latency degradation index when the lambda value is modified keeping ED and TXOP fixed. Figures 21 and 22 exhibit the throughput and latency degradation index when the detection threshold is modified keeping λ and TXOP fixed.

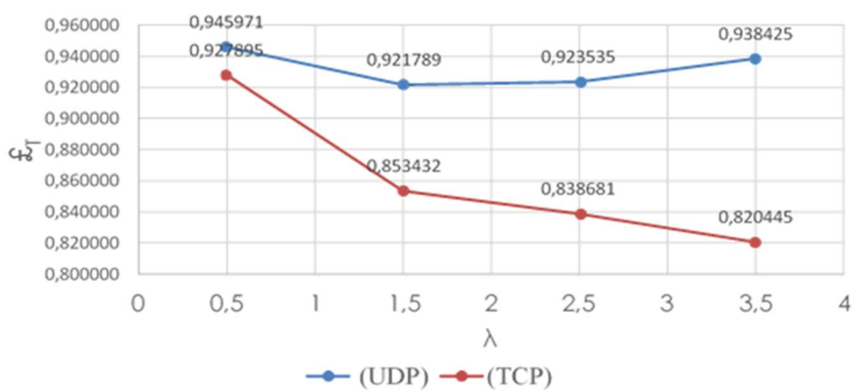

Figure 19. Throughput Degradation Index For Lambda Variation

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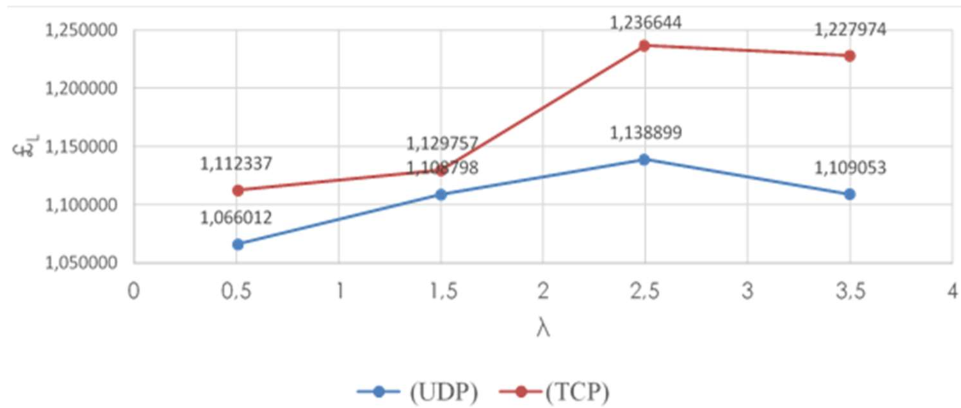

Figure 20. Latency Degradation Index For Lambda Variation

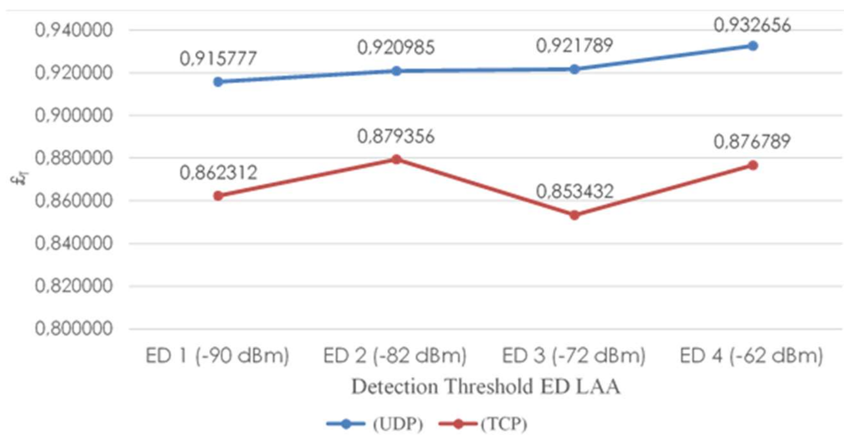

Figure 21. Throughput Degradation Index For Detection Threshold Variation

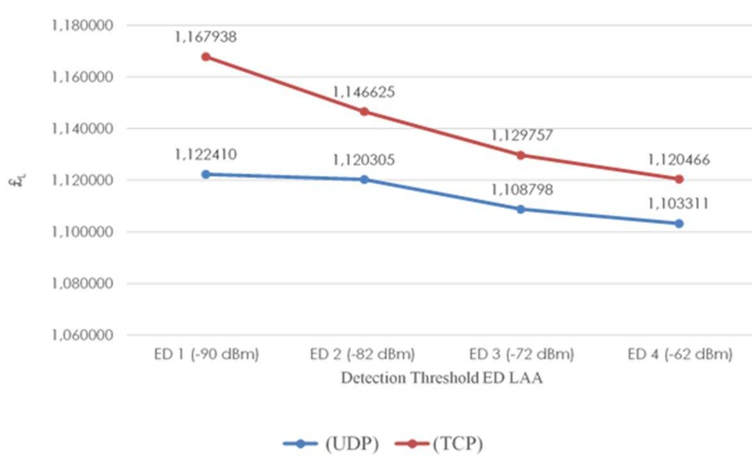

Figure 22. Latency Degradation Index For Detection Threshold Variation

According to the figures above, the LAA ED threshold, which reached the lowest degradation

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index £T was -62dBm; this result is the same used by Wi-Fi as recommended by the 3GPP TR36.889.

Besides, the simulations and degradation analysis pointed out a throughput degradation smaller than one (£T<1) in operator B (Wi-Fi) under coexistence with operator A (LAA).

Figures 23 and 24 exhibit the throughput and latency degradation index when the TXOP is modified keeping λ and ED fixed.

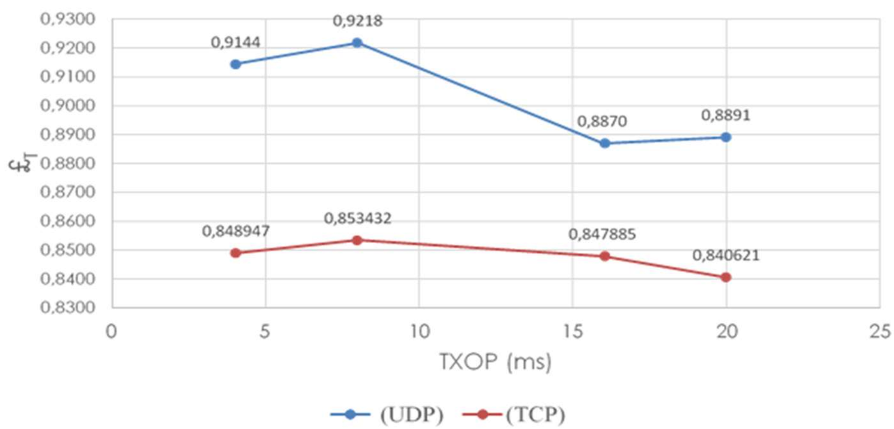

Figure 23. Throughput Degradation Index For TXOP Variable

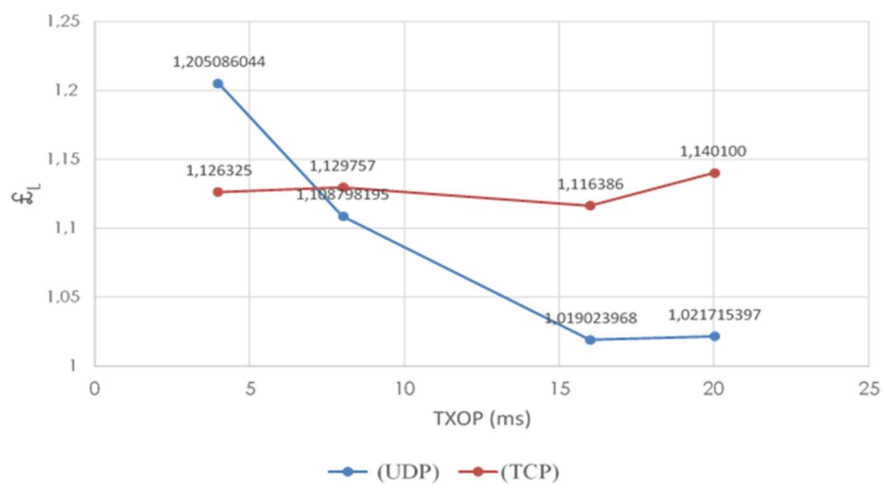

Figure 24. Latency Degradation Index For TXOP Variable

According to the information in the figures, the smallest degradation was obtained for a TXOP of 8 ms, as recommended by the 3GPP TR36.889.

4. CONCLUSIONS

The main contribution of this work is the fact of being able to define specific metrics of interest that allow an analysis of the coexistence between LTE and Wi-Fi, specifically a degradation index shown in equation (1). This parameter directly relates the Throughput and Latency with and without coexistence, simplifying complex models of previous literature [6][7]. So grant a helpful analysis, and comparison tool for the study case presented, leading in a Quality-of-Service model in a simple equation.

It assessed the Wi-Fi network performance focused on analyzing network throughput and latency, considering two operators and an indoor environment; initially, both operators transmit Wi-Fi, and then one operator (operator B) changes to LTE LAA. The degradation model analyzed for variation of lambda, LTE operational time, and ED threshold exhibited degradation in the network throughput for the Wi-Fi operator in coexistence with the LAA operator.

The throughput degradation is affected both the signal level as well as in upper transmission layers, reflecting different results for UDP and TCP FTP transmission.

Furthermore, the results of the coexistence evaluation need to improve the degradation model considering additional metrics such as jitter, as well as to be compared with real field measurements, where could be identified additional metrics. Unfortunately, LAA tests are only being announced by some operators in the USA and Korea.

As future work, the authors plan to analyze LTE access techniques that allow new LTE and Wi-Fi coexistence mechanisms in non-licensed bands beyond those given by Qualcomm and Ericsson.

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REFERENCES

[1] T. J. Barnett, A. Sumits, S. Jain & U. Andra,"Cisco Visual Networking Index (VNI) Update Global Mobile Data Traffice Forecast," *Cisco Vis. Netw. Index Updat. Glob. Mob. Data Traffic Forecast*, 2015, pp. 2015-2020

[2] Mathworks, "Accelerating the Development of Hardware Testbeds for 5G Wireless Systems" *The MathWorks,* 2016.

[3] Al-Dulaimi, S. Al-Rubaye, Q. Ni & E. Sousa, "5G Communications race: Pursuit of more capacity triggers LTE in unlicensed band", *IEEE Veh. Technol. Mag, vol. 10, nº 1*, 2015, pp. 43-51.

[4] MinTic, "Wi-Fi gratis,» Colombia Vive Digital, 12 Junio 2018". *Available: http://www.wifigratis.gov.co.*

[5] F. A. Zarta Escobar, "Modelo de afectación de calidad de servicio en redes Wi-Fi en coexistencia con redes LTE en banda no licenciada", *Tesis Maestría en Ciencias de la información y las comunicaciones,* 2017.

[6] A. Bhorkar, C. Ibars & P. Zong, "Performance analysis of LTE and Wi-Fi in unlicensed band using stochastic geometry", *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications,* 2015.

[7] W. J. Hillery, N. Mangalvedhe, I. Z. Kovács, R. Bartlett & Z. Huang, "A network performance study on LTE in unlicensed spectrum", *2015 IEEE Globecom Work. GC Wkshps 2015.*

[8] D. Malladi, "Best use of unlicensed spectrum", *Qualcomm Tecnologies,* 2016.

[9] Q. Chen, G. Yu & Z. Ding, "Optimizing Unlicensed Spectrum Sharing for LTE-U & Wifi Network Coexistence", *IEEE J. Sel. Areas Commun, vol. 34, nº 10,* 2016, *pp. 2562-2574.*

[10] LTE-U Forum, "LTE-U SDL Coexistence Specifications v1.3 (2015-10)" *vol. 0,* 2015, *pp. 1-10.*

[11] Samsung Electronics, "LTE-U Forum: UE Minimum Requeriments for LTE-U SDL" *vol. 0,* 2015*, pp. 0-68.*

[12] Samsung Electronics, "LTE-U CSAT Procedure TS V1.0" *vol. 0,* 2015, *pp. 1-7.*

[13] A. K. Sadek, T. Kadous, K. Tang, H. Lee y M. Fan, "Extending LTE to unlicensed band - Merit and coexistence*", 2015 IEEE International Conference on Communication Workshop (ICCW), London,* 2015.

[14] J. Zhou & M. Fan, "LTE-U Forum and Coexistence Overview" *Qualcomm, Washington,* 2015.

[15] Qualcomm Technologies Inc, "LTE-U Forum Technical Report Overview" *Qualcomm*, 2015.

[16] Alcatel-Lucent, "LTE-U Technical Report Coexistence Study for LTE-U SDL V1.0" *LTE-U Forum,* 2015.

[17] Qualcomm Technologies, "Qualcomm Research LTE in Unlicensed Spectrum: Harmonious Coexistence with Wi-Fi"*, Qualcomm Technologies, San Diego*, 2014.

[18] S. Saadat, D. Chen, K. Luo, M. Feng & T. Jiang, "License assisted access - Wi Fi coexistence with TXOP backoff for LTE in unlicenses band"*, China Communications, vol. 14, nº 3,* 2017, *pp. 1-14.*

[19] Qualcomm Technologies Inc, "Progress on LAA and its relationship to LTE-U and MulteFire", *Qualcomm,* 2016.

[20] N. Rupasinghe, & I. Guvenc, I. "Licensed-assisted access for WiFi-LTE coexistence in the unlicensed spectrum". 2014 IEEE Globecom Workshops, GC Wkshps 2014.

[21] P. De Santana, V. D. De Lima Melo y V. De Sousa, "Performance of License Assisted Access Solutions Using NS-3", *2016 International Conference on Computational Science and Computational Intelligence (CSCI), Vegas,* 2016.