

Article

Performance Modeling and Analysis of LTE/Wi-Fi Coexistence

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Abstract: In wireless communications, the fundamental challenge facing mobile operators nowadays is the scarcity of the spectrum and the license fees. Because of the increased traffic, critical performance analysis becomes important to overcome such issues. To tackle these issues and improve the network performance and capacity, a coexistence model of LTE and Wi-Fi with two virtual zones is suggested. The inner zone is the secondary zone, which represents Wi-Fi with an unlicensed spectrum to serve the best effort user data and the outer zone is the primary zone, which represents LTE with licensed spectrum to serve all data connections. The numerical solution of the model is presented using MOSEL-2 simulation and the mathematical solution is derived to validate the model. A threshold minimum bit rate established the user admission. Based on a priority level of the service, most of the traffic is served by the primary LTE zone, however, low priority traffic is moved from the primary LTE zone to the secondary Wi-Fi zone so that the traffic of the entire network is balanced. Although this coexistence sometimes harms LTE performance, the simulation results demonstrate the efficiency of the proposed model in balancing the load over the network, and, consequently, the network performance is improved.

Keywords: LTE; Wi-Fi; performance analysis; mathematical solution; coexistence; MOSEL-2



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1. Introduction

In the next generation of mobile broadband systems, such as long-term evolution (LTE) and LTE-Advanced, mobile operators are looking forward to increasing the capacity of their cellular networks by the utilization of the unlicensed spectrum available through other technologies, such as Wi-Fi. Therefore, nowadays, mobile operators are struggling to solve the problem of the deficiency of resources by increasing the capacity without affecting the quality of service (QoS). QoS means the ability to provide a certain level of performance to a data flow, i.e., blocking, delay, and utilization. Consequently, the research on performance analysis and modeling while integrating various technologies under different network scenarios is essential [1,2]. Additionally, having different technologies coexist to improve network performance is also considered as an important role to be well thought out by the researchers. As per the third generation partnership project (3GPP) [3], the IEEE 802.16 family of standards involved two technologies for the 4G wireless broadband systems, such as Advanced Long Term Evolution (Advanced LTE) and the Worldwide Interoperability for Microwave Access Release 2.0 (WiMAX 2.0). Considering the QoS of the network, multimedia services, such as data, voice-over IP, and video, are delivered through them. Assuming user mobility and adaptive coding and modulation techniques, studying the performance analysis, evaluation, and modeling of such systems remains very challenging because of multiple limitations and restrictions. The new era of 5G technology should be able to eliminate any restrictions imposed by the old technology, since the new technology provides more flexibility and adds new features to the old technology [4]. For this purpose, we present a new integration of LTE and Wi-Fi networks as a complementary solution to benefit from both technologies to achieve a better QoS for users, and hence a new path to 5G technology is initiated. In this regard, both technologies simultaneously

utilize the licensed and unlicensed spectrum. This means LTE technology works on the unlicensed band without affecting Wi-Fi performance.

As per the research conducted in [4,5], Qualcomm was the first who proposed the direct access of unlicensed bands in the downlink by LTE. Likewise, the analysis and research is focused only on the downlink where LTE directly accesses the unlicensed bands. LTE-Advanced was the leading nominee for 4G and it has been accepted to be the main standard for 4G by the International Telecommunication Union-Telecommunication (ITU-T). In the 3GPP meeting in March 2011 [3], this decision was confirmed and standardized. LTE is based on the orthogonal frequency division multiple access (OFDMA) modulation technique where data can be transmitted on narrow-band and orthogonal sub-carriers in the frequency domain and, therefore, resources can be shared among different users. Similarly, using Wi-Fi technology, the Access Point can connect different wireless devices, such as tablets, laptops, and smartphones.

The presented research in this paper extends the work already published at the IEEE conference [6]. In this extended version, the following points are considered:

- We revise the whole conference paper. Compared to the original paper, only 4% similarity is obtained.
- We revised the literature review with new references.
- We added information about the MOSEL-2 simulation.
- The mathematical formulation of the model is derived and introduced to validate the simulation results.
- All figures and tables are redrawn, and we revise the explanations to reflect the extension. Moreover, new tables and figures are added.

The rest of the paper is organized as follows: Section 2 presents the related work; Section 3 presents the modeling, which includes five subsections (LTE/Wi-Fi model integration in Section 3.1, modeling assumptions in Section 3.2, the mathematical formulation of the model in Section 3.3, LTE QoS services and applications in Section 3.4, and the MOSEL-2 solution in Section 3.5); the simulation results and discussions are presented in Section 4; and the conclusions and future work are presented in Section 5.

2. Related Work

In wireless communication technology, Wi-Fi stands for “wireless fidelity”; it is the name of a wireless technology protocol that allows us to communicate data wirelessly. LTE stands for “long-term evolution”, which is the fourth generation wireless broadband technology standard. LTE is a very reliable technology with high speed and top security for smart devices and smart phones. Although Wi-Fi is the preferred technology of different enterprises, the LTE/Wi-Fi debate took place between different enterprises, concerning which form of technology should be used. Following the technological developments and because of the need for Internet connection that is reliable with excellent performance, maximum capacity and Internet of Things (IoT) applications, many enterprises recognized the need for cellular networks, such as LTE. Both LTE and Wi-Fi provide data access over the Internet and both use the wireless spectrum, however, they are varied in terms of performance, speed, security, coverage, and capacity. Nevertheless, in our daily life activities, we rely on both technologies in communication, news, entertainment, health, education, and other activities. Evidently, when LTE is presented to share an unlicensed spectrum with other technologies, such as Wi-Fi, some issues appear since LTE needs to have full control of the spectrum during its data transmission [7]. Therefore, the interoperability model that provides us with the integration between both technologies has a significant advantage on the wireless technology, as LTE technology with a licensed spectrum incorporates Wi-Fi technology that provides an unlicensed spectrum.

3GPP considered and adopted LTE and LTE-Advanced as leading cellular mobile communication services, and they are intensively studying the different coexistence scenarios with other technologies [8–23]. The research [8–21] focused on improving the network performance, while both technologies coexisted, rather than the individual performance

of each technology. Some other research [22,23] focused on the effect of the coexistence principle on both technologies. Our research combines both objectives, as we are interested in studying the effect of coexistence on each technology, however, our primary focus is to balance the traffic load among both technologies so that the overall network performance and capacity are maximized.

Regarding the first group of research, in [8], the coexistence of Wi-Fi and LTE is studied based on a human-centric approach, for which human satisfaction is the major concern in this research work. User satisfaction is not preserved by the coexistence of both technologies, however, by performance modeling and simulation under semi-adaptive partitioning, this level of satisfaction is facilitated and, therefore, the authors conclude that there is no advantage to the coexistence between Wi-Fi and LTE when the unlicensed spectrum is partitioned. This means there is a possibility of deploying Wi-Fi without LTE in the unlicensed spectrum. Forming a coexistence gap in the time and space domain was the idea in [9], where the authors provide a flexible collaboration among LTE and Wi-Fi networks. The integration between both technologies is presented in the demonstrated simulation results. It dramatically improved network throughput and channel delay, taking into consideration that the achieved improvement in performance depends on some network configurations, such as the assumed distance between LTE and Wi-Fi networks. In [10], the authors proposed a new model of fair coexistence for LTE and Wi-Fi, so that the Carrier Sensing Adaptive Transmission mechanism can be optimized. Additionally, the authors presented a throughput Optimal Channel Selection algorithm for LTE and, according to the demonstrated numerical results, it is shown that the system throughput is dramatically improved. In [11], cross-technology communication between LTE and Wi-Fi is activated by a new technique called LtFi based on two steps. The first step is to use a side channel among both technologies to generate a bi-directional connection and the second step is to use the identification information to adjacent Wi-Fi nodes, which is used in a subsequent step to create a bi-directional control channel over the wired backhaul. The complete description of the LtFi system is presented in [11]. The provided simulation results show that even if the network is congested, the transmission rate of the data is enhanced. Other research [12] focuses on the LTE and WiMAX performance, by considering various antenna diversity for frequency division and time division multiplexing concerning the maximum throughput of the physical layer. In this regard, the authors considered similar configurations for both technologies to compare their performance. It was found that LTE produces a better performance than WiMAX in all circumstances. In [13], the authors considered that studying the coexistence principle in the unlicensed spectrum between LTE and other technologies, such as Wi-Fi, could be a very interesting topic for researchers. A multi-objective optimization framework to study LTE and Wi-Fi performance in a separate matter and to balance the performance of both technologies concerning the unlicensed spectrum is proposed in [14]. The genetic algorithm is used to guarantee the optimization of the throughput for both technologies, as well as the Wi-Fi average packet delay. Multiple deployment scenarios of the coexistence on 5 GHz between Wi-Fi and long-term evolution-licensed assisted access are demonstrated in detail through an extensive survey presented by the authors in [15]. Various topics are discussed in the survey, such as the performance comparison between both technologies, the carrier aggregation of LTE while using an unlicensed spectrum, the medium-access control protocol for both technologies, and the co-channel interference principle. Additionally, the authors also considered the most important challenges that occurred while both technologies coexisted. In both [16,17], it is shown that the coexistence between LTE and Wi-Fi has a constructive effect on network performance. Both papers emphasized the fact that the hotspot range, which limits the active users in the cell, is affected by the end-user power rather than the access point. Consequently, any request forwarded to the access point has a constructive effect on the overall performance of the network. Licensed-assisted access (LAA) is a tremendous endeavor conducted by the 3GPP project to approve the standardization of the LTE operation in Wi-Fi unlicensed bands. The orthogonal coexistence of LAA with Wi-Fi

unlicensed spectrum is examined in [18]; the coexistence is based on a listening-before-talk setup. The main objective was to maximize the QoS of end-users in LAA and, at the same time, guard Wi-Fi users. Given the simulation results and QoS metrics, the effectiveness of the suggested scheme is shown. To optimize the resource allocation of the unlicensed spectrum in LTE systems, the authors in [19] suggested an algorithm called Multi-Armed Bandit (MAB) to estimate the unused white space of the unlicensed spectrum due to the inefficient use of the resources. To show the effectiveness of the work, the authors compared the results with other algorithms in the literature. A sub-carrier nulling scheme is suggested in [20]. This scheme is based on the idea that Wi-Fi nodes apply sub-carrier sensing on LTE nodes that are working at the same frequency with no overlap between them. The provided simulation results show that the proposed scheme increases the coexistence performance and provides fairness of more than 90%. A time-sharing power resource virtualization technique is suggested in [21]. The authors assumed that utilizing the unlicensed channels used by Wi-Fi networks in LTE networks becomes a new challenge in the research field. Therefore, they assumed in this technique a shared access point between both technologies. Based on this, a mixed-integer non-linear programming problem is formulated and solved. As per the provided numerical results, it is shown that power saving can be improved using the virtualization technique, which is the main objective of the present work.

The authors in [22] emphasized the fact that, while LTE and Wi-Fi coexist, multiple issues and challenges might appear and, therefore, the authors investigated those issues and studied the performance of both technologies via simulations. As per the given performance results, it is shown by the authors that the coexistence deployment harms Wi-Fi performance more than LTE performance. In addition to coexistence, when authors consider the reuse principle of sub-frames in LTE, which is referred to as blank sub-frames, where LTE is not transmitting, it is shown that the Wi-Fi throughput improves 50 times more with this principle. The coexistence of the IEEE 802.11n standard of Wi-Fi with LTE, with FTP traffic under the Time Division Duplex (TDD), is investigated in [23] through a multi-cell scenario. The authors conducted an analysis to study the performance of the network while both technologies were coexisting. The performance results show that the performance of Wi-Fi is negatively affected, while LTE performance is not.

Linked to other people's works, the following points demonstrate the author's contributions:

- The proposed model in this research demonstrates the fact that although the integration between both technologies might have a negative effect on the LTE performance, it improves the performance of the network by balancing the load over the whole network.
- In this current research, we propose an interoperability model of coexistence among LTE and Wi-Fi. The cell and network performance are studied based on the consequences of integrating the two technologies. Moreover, comparative results are prepared and demonstrated to show the effect of this integration and coexistence on LTE performance, because some authors' results in the literature reflect the positive effect of this integration on LTE performance, while other results alternatively reflect the negative effect.
- The main goal of the current research is to invent a new methodology to help mobile operators to estimate the proper performance measures that help to compare different interoperability models under various deployment and integration scenarios.
- As per the team effort and experience in developing and solving the suggested model, numerically by the simulation and analytically by the mathematical solution, this new methodology can be used as a new tool that has an important commercial value for mobile operators. Therefore, the proper utilization of the above methodology and associated tool can help in proposing new deployment and integration scenarios to accomplish better network performance by maximizing the capacity of the network as well as achieving better QoS for the end-user.

3. Modeling

3.1. LTE/Wi-Fi Model Integration

Wireless broadband access technology can provide end-users with diverse services through multiple technologies, while maintaining a better performance and quality of service of the network. On the other hand, the core objective is to offer an interoperability solution that includes a deployment of different technologies to accomplish the enhanced performance of the network, so that the end-user can enjoy the service at any time and anywhere [24,25]. By suggesting the LTE/Wi-Fi interoperability model and incorporating different technologies, shared characteristics are achieved for the benefit of end-users in diverse non-line-of-sight environments. The proposed scenario is to obtain a hotspot unlicensed Wi-Fi zone surrounded by a set of licensed LTE zones, in which users can have endless connectivity in different conditions, as shown in Figure 1. LTE is the primary macro-cell zone (i.e., zone 2) with a licensed spectrum to manage all the data connections, while Wi-Fi is the secondary micro-cell zone with an unlicensed spectrum to handle the best effort user data. Considering the above assumptions, the following scenario works: allocating best effort traffic via the Wi-Fi interface and QoS-sensitive traffic via the LTE interface boosts user involvement in both traffic classes by monitoring the large bandwidth available on the Wi-Fi link and releasing resources on the LTE link.

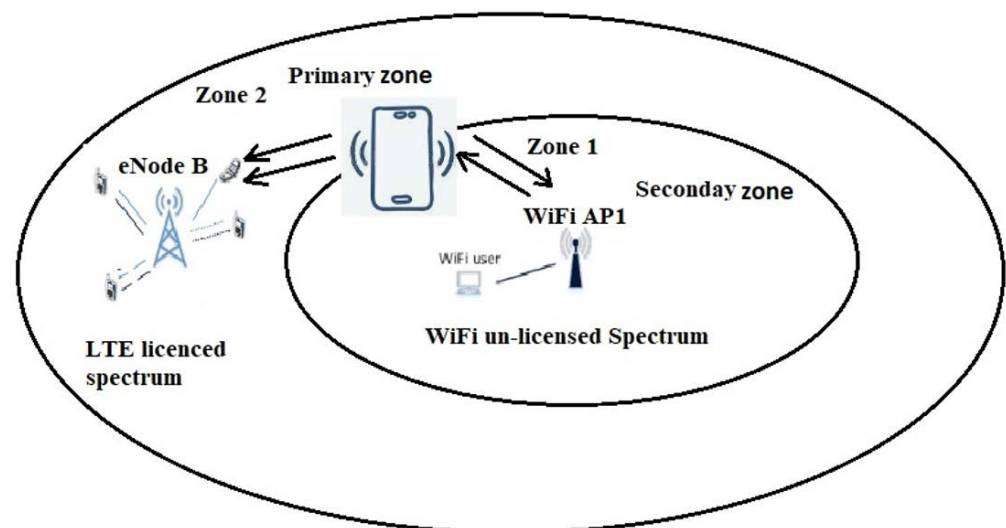


Figure 1. LTE/Wi-Fi integration/coexistence model.

3.2. Modeling Assumptions

1. A maximum bit-rate capacity is assumed for the whole cell. However, as per the zone structure, the capacity is subject to the modulation level and the number of users in the cell. Only licensed bands employ LTE technology, however, LTE is still able to share the unlicensed bands' resources provided by Wi-Fi technology, taking into consideration that the admission of the request is still eliminated by the minimum bit-rate threshold.
2. The Opportunistic Supplemental Downlink method is proposed [25] to assure a flexible evolution and deployment between LTE and Wi-Fi technologies without degrading the network performance. Based on this method, the unlicensed band can be perceived as an opportunistic carrier to be utilized when the licensed carrier is completely utilized. Therefore, the limitation on accessing each technology is based on the minimum bit-rate threshold to be satisfied.
3. According to the modulation principle of LTE, which is based on OFDM, two zones are assumed in this study, as shown in Figure 2. According to the OFDM signal, there is a potential to select between the modulation types of LTE signals [26–29]. Zone 1,

with 64QAM, represents the secondary zone (inner zone) and zone 2, with 16QAM, represents the primary zone (outer zone), as shown in Figure 2.

4. For the arrival rate to the cell, this is assumed to be the Poisson arrival with the inter-arrival time λ , and it is related to the areas of the zones ($\alpha_i \lambda, i = 1, \dots, \text{zone } i$), the density of the users in zone i (α_i), and the modulation schemes used in each zone.
5. For a specific QoS assurance, a user admits to the cell if a minimum-threshold bit rate is satisfied. This condition is for both the LTE and Wi-Fi technologies.

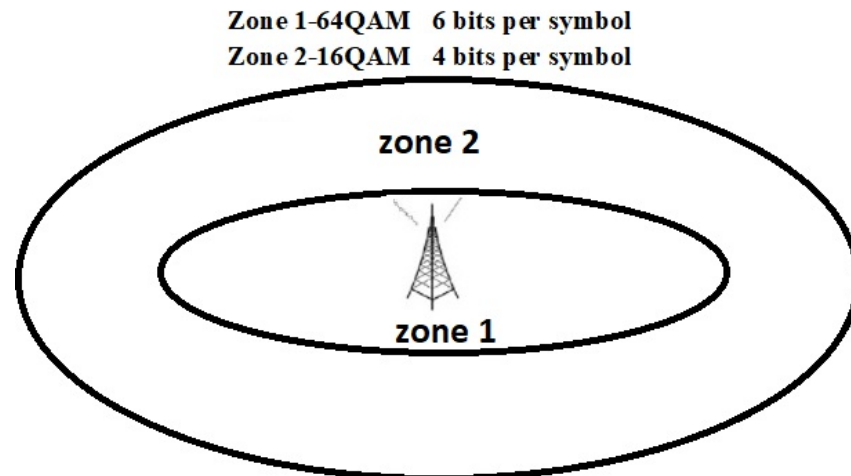


Figure 2. LTE cell divided into two zones.

3.3. Mathematical Formulation of the Model

Based on the MOSEL-2 solution, the following mathematical formulation of the model is provided. Table 1 contains the list and descriptions of the symbols used in the model formulation.

Assume the following parameters:

$NWB_Zi(t)$: the number of web-browsing sessions in zone i at time t . $i = 1, \dots, k$, k is the number of zones.

$NSTR_Zi(t)$: the number of video streaming sessions in zone i at time t . $i = 1, \dots, k$

$NVOLTE_Zi(t)$: the number of voice calls sessions in zone i at time t . $i = 1, \dots, k$

Therefore, we define a system state at a given point of time as a vector $S(t)$:

$$S(t) = (NWB_Zi(t), NSTR_Zi(t), NVOLTE_Zi(t)) \quad (1)$$

Represents the stochastic process, which is based on the time, t , where $i = 1, \dots, z$, representing a specific zone.

Moreover, the total number of users in all zones is given by:

$$N_{TOTAL} = \sum_{i=1}^k (NWB_Zi + NSTR_Zi + NVOLTE_Zi) \quad (2)$$

Given the above system state, the stochastic process of the system represents a multi-dimensional Continuous Time Markov Chain Process (CTMCP) to solve a multi-dimensional transition matrix Q .

$$Q = ||Q_{lm}|| = \begin{vmatrix} Q_{00} & Q_{01} & Q_{02} \\ Q_{10} & Q_{11} & Q_{12} \\ \vdots & \vdots & \vdots \\ Q_{l0} & Q_{l1} & \dots \end{vmatrix} \quad (3)$$

where l and m are the two states of the process and the transition matrix of the system Q can then be expressed as $Q = \{q_{lm}\}$, where q_{lm} is the transition rate from state l to state m . l ,

$m = 0, \dots, R$, where R is the total number of possible states in the system. Assuming that the number of gained states is predetermined, then the result is a predetermined square matrix, for which the rows and the columns are equal. The provided solver attached to the MOSEL-2 language solves this system state.

Table 1. Symbols used in the mathematical formulation of the model.

Symbol	Description	Symbol	Description
k	The total number of zones	$MEAN_{VOLTEz}$	The mean number of users related to the VOLTE service in the respected zone
$NWB_Zi(t)$	The number of web-browsing sessions in zone i at time t	$MEAN_{VOLTE_ALL}$	The mean number of users related to the VOLTE service in all zones
$NSTR_Zi(t)$	The number of video streaming sessions in zone i at time t	N_z	The number of users in each zone related to each service
$NVOLTE_Zi(t)$	The number of voice calls sessions in zone i at time t	P_z	The probability of being in the respected zone for a given service
$S(t)$	A system state at a given point of time	$MEAN_z$	The mean number of users in each zone with respect to each service
N_{TOTAL}	The total number of users in all zones	$MEAN_{Total}$	The mean total number of users in all zones
Q	The transition matrix	$P_{blocking}$	New call-blocking probability
q_{lm}	The transition rate from state l to state m	P_{loss}	Loss probability of the call
R	The total number of possible states	Max_Cell_Cap	Maximum assumed capacity in the cell
WB	Web-browsing service category	$Zone1_{Cap}$	Maximum assumed capacity for zone 1
STR	Video streaming service category	$Zone2_{Cap}$	Maximum assumed capacity for zone 2
$VOLTE$	Voice over LTE service category	WB_{ratio}	The ratio of the WB service out of 100%
ABR_i	Average bit rate of zone i	STR_{ratio}	The ratio of STR service out of 100%
BR_{min}	Minimum required threshold bit rate	$VOLTE_{ratio}$	The ratio of the VOLTE service out of 100%
λ	Arrival rate	$TMBR_{cell}$	Mean total bit rate in the cell
α_i	The density of the users in zone i	ABR_{cell}	Average bit rate in the cell
BR_i	Bit rate of zone i	MCC	Maximum cell capacity
$MEAN_{WBz}$	The mean number of users related to the WB service in the respected zone	$AABR_z$	Aggregate average bit rate per zone
$MEAN_{WB_{ALL}}$	The mean number of users related to the WB service in all zones	$AABR_{WB_z}$	Aggregate average bit rate per WB service in the respected zone
$MEAN_{STRz}$	The mean number of users related to the STR service in the respected zone	U	Utilization
$MEAN_{STR_{ALL}}$	The mean number of users related to the STR service in all zones		

The rules for generating the transition states of the matrix are presented in Table 2.

Table 2. Rules for generating the transition states of the matrix.

Rules	Current State	Next State	Condition	Transition
New arrival of WB to zone i	$NWB_Zi, NSTR_Zi, NVOLTE_Zi,$	$NWB_Zi+1, NSTR_Zi, NVOLTE_Zi,$	$ABR_i \geq BR_min$	$\lambda * WB * \alpha i$
New arrival of STR to zone i	$NWB_Zi, NSTR_Zi, NVOLTE_Zi,$	$NWB_Zi, NSTR_Zi+1, NVOLTE_Zi,$	$ABR_i \geq BR_min$	$\lambda * STR * \alpha i$
New arrival of WB to zone i	$NWB_Zi, NSTR_Zi, NVOLTE_Zi,$	$NWB_Zi, NSTR_Zi, NVOLTE_Zi+1,$	$ABR_i \geq BR_min$	$\lambda * VOLTE * \alpha i$
WB departure from zone i	$NWB_Zi, NSTR_Zi, NVOLTE_Zi,$	$NWB_Zi-1, NSTR_Zi, NVOLTE_Zi,$	$NBW_Zi \geq 1$	$\frac{\mu * WB * ((BR_i/BR1))/N_TOTAL}{((BR_i/BR1))/N_TOTAL}$
STR departure from zone i	$NWB_Zi, NSTR_Zi, NVOLTE_Zi,$	$NWB_Zi, NSTR_Zi-1, NVOLTE_Zi,$	$NSTR_Zi \geq 1$	$\frac{\mu * STR * ((BR_i/BR1))/N_TOTAL}{((BR_i/BR1))/N_TOTAL}$
VOLTE departure from zone i	$NWB_Zi, NSTR_Zi, NVOLTE_Zi,$	$NWB_Zi, NSTR_Zi, NVOLTE_Zi-1,$	$NVOLTE_Zi \geq 1$	$\frac{\mu * VOLTE * ((BR_i/BR1))/N_TOTAL}{((BR_i/BR1))/N_TOTAL}$

The MOSEL-2 simulation generated the following performance indicators:

1. Mean total number of users in all zones:

First, we need to calculate the mean number of users related to each service in each zone and all zones:

$$MEAN_{WBz} = (N_{z-WB} * P_{z-WB}) \quad (4)$$

$$MEAN_{WB_ALL} = \sum_{z=1}^k (N_{z-WB} * P_{z-WB}) \quad (5)$$

$$MEAN_{STRz} = (N_{z-STR} * P_{z-STR}) \quad (6)$$

$$MEAN_{STR_ALL} = \sum_{z=1}^k (N_{z-STR} * P_{z-STR}) \quad (7)$$

$$MEAN_{VOLTEz} = (N_{z-VOLTE} * P_{z-VOLTE}) \quad (8)$$

$$MEAN_{VOLTE_ALL} = \sum_{z=1}^k (N_{z-VOLTE} * P_{z-VOLTE}) \quad (9)$$

where $z = 1, \dots, k$; k is the total number of zones.

N_z : is the number of users in each zone related to each service.

P_z : is the probability to be in this zone for a given service.

Then, we calculate the mean number of users in each zone:

$$MEAN_z = \sum_{z=1}^k (MEAN_{WB_z} + MEAN_{STR_z} + MEAN_{VOLTE_z}) \quad (10)$$

Therefore, the mean total number of users in all zones is given as:

$$MEAN_{Total} = \sum_{z=1}^k (MEAN_z) \quad (11)$$

2. New call-blocking probability: the probability to block the new user from being admitted to the system. This probability is given as:

$$P_{blocking} = \sum_{i=0}^N P_i * B(P_i) \quad (12)$$

where $B(P_i)$ is a constant, which is equal to one, if the average bit rate of the user is not satisfied, which means that the average bit rate for the given user is less than the minimum bit rate assumed for the cell, otherwise the value of $B(P_i)$ will be zero. P_i is the probability to be in a state i . N is the number of users in the cell.

3. Loss probability: the probability of dropping an active user in the system because the average bit rate of the user is dropped down below the threshold value assumed in

the system. Evidently, this type of probability should be minimized in the system, as blocking a new user is less harmful to the system than dropping the user who is already admitted and active in the system.

$$P_{loss} = \sum_{i=0}^N P_i * L(P_i) \quad (13)$$

where $L(P_i)$ is a constant, which is equal to one if the average bit rate of the user is higher than the minimum bit rate assumed for the cell, otherwise it is zero. However, for some reason, the average bit rate of this user is suddenly dropped due to technical reasons, which result in the loss of the call.

4. Mean total bit rate in the whole cell:

According to the LTE modulation,

The average bit rate of zone 1 is calculated as follows:

First, we calculated the bit rate in each zone as follows (assuming that the inner zone is always given the maximum achievable bandwidth because it represents the dense area with more traffic density than the outer zones). Based on the assumed modulation technique (in our case, two modulation levels are assumed as a compensation for the signal strength and quality), the maximum achievable bit rate in each zone is:

$C_i = 2 * C_{i+1}, i = 1, \dots, Z - 1$. Therefore,

The bit rate in zone 1 (inner zone): $BR_1 = Max_Cell_Cap$.

The bit rate in zone 2 (outer zone): $BR_2 = Max_Cell_Cap/2$.

Next, we calculate the maximum capacity in each zone:

The maximum capacity of zone 1:

$$\begin{aligned} Zone1_{Cap} &= (Max_{CellCap} / Min_{bitrate}) \\ Zone2_{Cap} &= (Zone1_{Cap} / (Min_{bitrate} * BR_2 / BR_1)) + 1 \end{aligned}$$

The average bit rate of zone 1 is given as:

$$ABR_1 = \left(\frac{BR_1}{BR_2} \right) * \left(\frac{BR_2}{N_{TOTAL} + 1} \right) \quad (14)$$

The average bit rate of zone 2 is given as:

$$ABR_2 = \left(\frac{BR_2}{N_{TOTAL} + 1} \right) \quad (15)$$

First, we calculate the total bit rate per zone:

$$TBR_z = ((zone_zCap * WB_{ratio}) + (zone_zCap * STR_{ratio}) + (zone_zCap * VOLTE_{ratio})) * ABR_z \quad (16)$$

where z is the zone number: $z = 1, \dots, k$ and k is the number of zones.

ABR_z is the average bit rate per zone.

Then, the mean total bit rate in the whole cell is:

$$TMBR_{cell} = \sum_{z=1}^k TBR_z \quad (17)$$

5. Utilization (U):

$$U = \frac{TMBR_{cell}}{MCC} \quad (18)$$

$TMBR_{cell}$ = Mean total bit rate in the cell.

MCC = Maximum cell capacity.

6. Average bit rate in the whole cell:

$$ABR_{cell} = \frac{TMBR_{cell}}{MEAN_{Total}} \quad (19)$$

7. Delay:

$$Delay = \frac{ABR_{Cell}}{MCC} \quad (20)$$

8. Throughput:

$$Throughput = TMBR_{cell} \quad (21)$$

9. Aggregate average bit rate per zone:

$$AABR_z = \sum_{z=1}^k ABR_z \quad (22)$$

10. Aggregate average bit rate per service in each zone:

$$AABR_{WB_z} = MEAN_{WB_z} * ABR_z \quad (23)$$

3.4. LTE QoS Services and Applications

The LTE QoS class indicator (QCI) specifications, alongside the desired priorities for each class of service, are presented in Table 3 [26,27]. By observing Table 3, one can notice that for a specific service type (either guaranteed bit rate (GBR) or non-guaranteed bit rate (non-GBR)) a priority is specified. Each resource type is related to a group of QCIs. Regarding the performance measures, such as the packet error loss and packet delay budget, they are given a minimum threshold value to be achieved to satisfy the required performance for the LTE network. For example, regarding the route between the UE and the gateway, a conversational video of a value of 2 for the QCI must have a priority of 4, a packet error loss rate less than 10^{-3} , and a packet delay less than 150 ms.

Although our investigations were limited to three service categories, in theory, the number of services can be greater, assuming that three types of service categories is common in the literature; however, in our model, increasing the number of service categories maximizes the state space and leads to a state space explosion issue. Agreeing with [6], in the study, the following classes of service are considered:

1. The web browsing (WB) service: the service belongs to the type of content one can download from the internet, such as files, pictures, music, and movies. A 60% ratio of the total traffic is assumed in the study for this type of service, as most of the applications on the Internet are content-download based and the bandwidth required depends on the QoS that needs to be satisfied for this content. Therefore, to guarantee maximum reliability for the transmitted and received packets for this type of service, a reliable TCP protocol is considered.
2. The voice-over IP over LTE (VoLTE) service: although little bandwidth is required for this kind of service, it is given high priority. It is called the voice-over-Internet protocol over LTE. In this study, the VoLTE (voice-over LTE) name is assumed for this type of service. Emergency calls (e.g., 112) are the best example, considering that each country has a different code for their emergency call. A 10% ratio of the total traffic is assumed for this service, as it is only required for rare emergency cases.
3. The video streaming (STR) service: 30% of the total traffic ratio is given to this type of service. Video streaming requires a reliable connection with a guaranteed QoS. To achieve this reliability, the availability of a large bandwidth is vital.

Table 3. QCI specifications for LTE [29]. (© 2022 - 3GPP™ deliverables and material are the property of ARIB, ATIS, CCSA, ETSI, TSDSI, TTA and TTC who jointly own the copyright in them. They may be subject to further modifications and are therefore provided to you "as is" for information purposes only. Further use is strictly prohibited).

QCI	Resource Type	Priority	Packet Delay Budget (NOTE 1)	Packet Error Loss Rate (NOTE 2)	Example Services
1 (NOTE 3)	GBR	2	100 ms	10^{-2}	Conversational voice
2 (NOTE 3)		4	150 ms	10^{-3}	Conversational video (live streaming)
3 (NOTE 3)		3	50 ms	10^{-3}	Real-time gaming
4 (NOTE 3)		5	300 ms	10^{-6}	Non-conversational video (buffered streaming)
5 (NOTE 3)	Non-GBR	1	100 ms	10^{-6}	IMS signaling
6 (NOTE 4)		6	300 ms	10^{-6}	Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, and progressive video)
7 (NOTE 3)		7	100 ms	10^{-3}	Voice Video (live streaming) Interactive gaming
8 (NOTE 5)		8	300 ms	10^{-6}	Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, and progressive video)
9 (NOTE 6)		9			

3.5. MOSEL-2 Simulation

The proposed model is analyzed via MOSEL-2 simulation, which is an extended version of the original MOSEL [1]. The new MOSEL-2 version is improved and updated to have the possibility to model inter-arrival and service-time distributions that are not only exponential, but also have non-exponential behavior. Conducting simulation with MOSEL-2 language makes life easy, and therefore the proposed model can be easily solved using a programming language that is easy to understand and apply because it is very similar to C language. Using MOSEL-2, the model that is given graphically as a queueing model or Petri net can be simply solved by MOSEL-2, then the associated state space is generated, the stochastic process is derived, and then MOSEL-2 provides a numerical solution that encompasses all the desired performance parameters. Fortunately, in a user-friendly environment, the figures can be formatted and prepared with easy steps by the intermediate graphical language (IGL) package, which is linked with MOSEL-2 upon installation. The old and new versions of MOSEL are frequently used by the group members and other researchers in the performance evaluation and modeling of queueing networks and the new generation of wireless mobile networks (i.e., 2G, 3G, 4G, and 5G). Recently, MOSEL-2 was used to model 4G and 5G mobile networks [6,24,25,30–32]. Figure 3 explains the steps of the model solution by MOSEL-2, considering that MOSEL-2 is only operational via the Linux operating system. For more information about the license and installation procedure, please see [1].

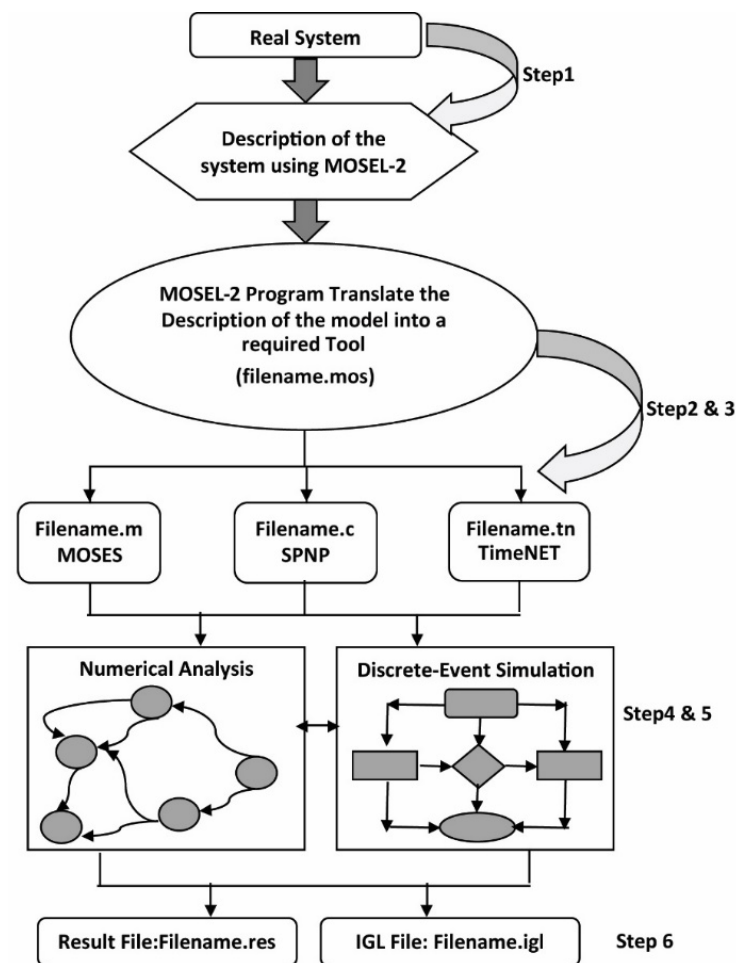


Figure 3. MOSEL-2 steps for model solution.

According to Figure 3, the following steps describe how the simulation model is developed:

- Step 1: the high-level system description is prepared with the MOSLE-2 tool in a simple C-like language, as shown in Figure 3. The description of the model is saved as “filename.mos”, where the desired performance measures are specified. Without the programmer interaction, the described model is passed to the evaluation environment, where all the following steps are performed.
- Steps 2 and 3: the model is translated into a specific tool for producing the input file via the MOSEL-2 environment. This tool can be the C-based Stochastic Petri Net tool (C-Based SPNP) [33] or TimeNet [34]. After choosing a specific tool, MOSEL-2 environment calls the tool.
- Steps 4 and 5: via different command-line options, the input file is processed by the tool in two different methods:
 - a. Numerical analysis: during this analysis, the complete state space of the system is generated, based on the semantic rules of the modeling language. The obtained semantic model is attached to the stochastic process. Afterwards, the available numerical solution algorithms solve the stochastic process.
 - b. Simulation: via discrete event simulation, the tool assesses the model with no need to generate the state space.
 - c. The generated results by discrete event simulation or numerical solution are saved in a file following the tool structure.
- Step 6: the MOSEL-2 environment analyzes the output developed by the tool using a command line to provide the output results in a text file with an extension (filename.res). This file contains all the results of the described performance measures.

Now, another file is generated with an extension (filename.igl), if the user needs the results in a graphical view.

4. Simulation Results and Discussion

Once MOSEL-2 language solves the model, the associated IGL package generates the numerical results. Table 4 shows the assumed simulation parameters. The simulation was run for different offered bit-rate values and by changing different parameters, until a steady-state point of the solution was reached, where results no longer change. All demonstrated results are shown against the total offered bit rate (Mbit/s). A 95% confidence interval is calculated for some results and the detailed parameters of the confidence interval are presented in Table 5.

Table 4. Simulation parameters.

Parameter	Value
Zones/cell, k	2
Web browsing ratio	0.60
Voice-over LTE ratio	0.10
Video streaming ratio	0.30
Web-browsing session size	10 Kbytes
Video streaming session size	50 Kbytes
Voice-over LTE session size	300 Kbytes
Maximum cell capacity	10 Mbit/s
Call rate/traffic load, λ	0.42–37.6 Mbit/s
Alpha 1 (density of the users in zone 1), α_1 (ratio of zone 1)	0.60
Alpha 2 (density of the users in zone 1), α_2 (ratio of zone 2)	0.40
Minimum bit rate in the cell (threshold)	1 Mbit/s
Service rate, web browsing (WB)	8 sessions/s
Service rate, video streaming (STR)	40 sessions/s
Service rate, voice-over LTE (VOLTE)	240 sessions/s
Maximum bit rate of zone 1	10 Mbit/s
Maximum bit rate of zone 2	5 Mbit/s

Table 5. The 95% confidence interval parameters.

Performance Parameters	Lower Bound (UP)	Upper Bound (LB)
Blocking probability	0.0002	0.0004
Utilization	0.47	0.91
Delay	86.97	138.79
Throughput	4.57	8.77

Two groups of results are demonstrated in this section. The first group encompasses the results to demonstrate LTE, Wi-Fi performance, as well as the overall cell performance against different types of services (Figures 4–9). All results are shown for different performance parameters against the total offered bit rate (Mbit/s). Moreover, LTE simulation results attained by MOSEL-2 are compared with the mathematical solution to validate the results. Three types of services are considered in the analysis: VOLTE, WB, and STR. In the analysis, a priority is assigned to VOLTE, as this service is crucial and needs to be urgently processed. The aggregate average bit rate is demonstrated in Figure 4, for all the suggested services in the inner zone (zone 1). Given the highest priority for the VOLTE service, it can be clearly observed in Figure 4 that the aggregate average bit rate (AABR) achieved results are maximized for VOLTE compared to the other services. Exciting results can also be observed in Figure 4 for the WB and STR services. Looking at Figure 4, one can notice that, below a 25 Mbit/s offered bit rate, the performance of STR regarding AABR is much better than WB, as the offered bit rate grows beyond the 25 Mbit/s performance of the WB improved accordingly.

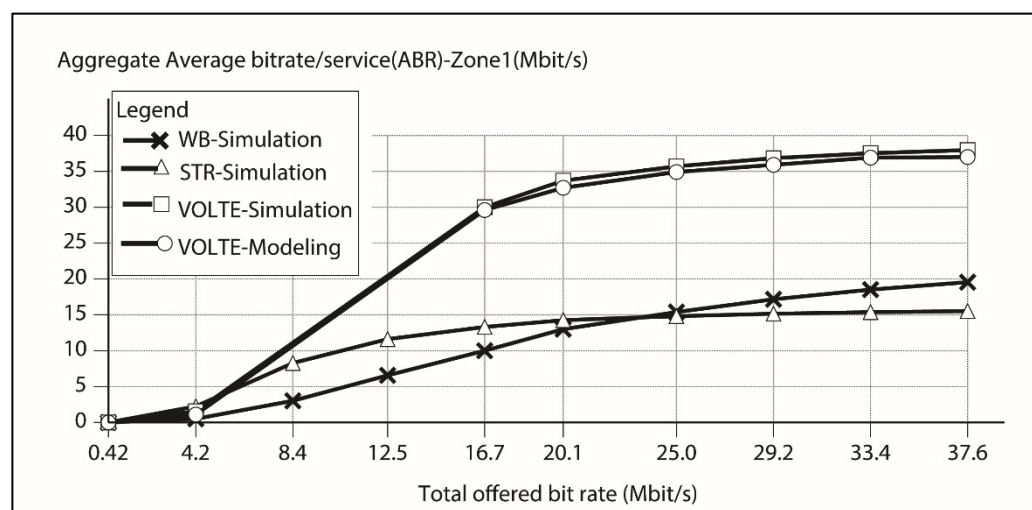


Figure 4. Zone 1: aggregate average bit rate.

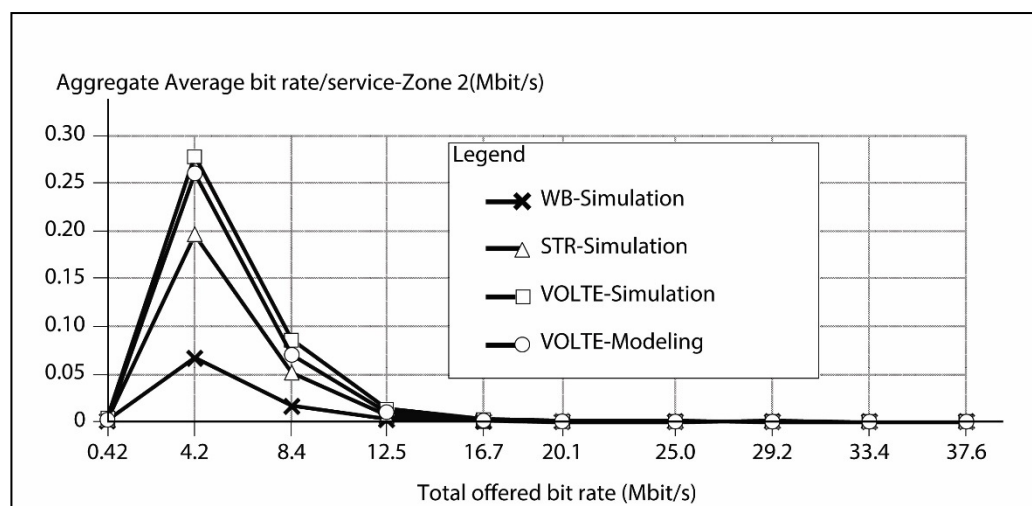


Figure 5. Zone 2: aggregate average bit rate.

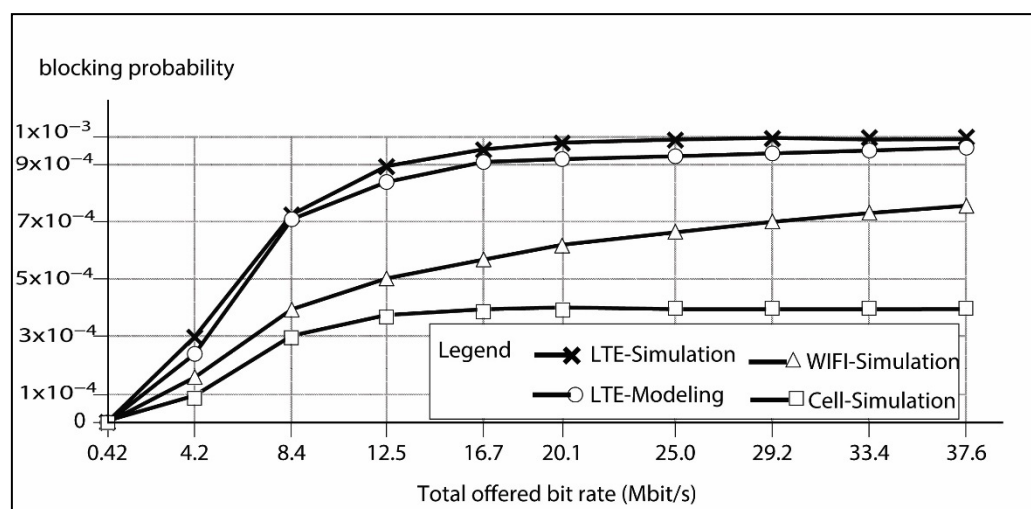


Figure 6. Blocking probability with the coexistence.

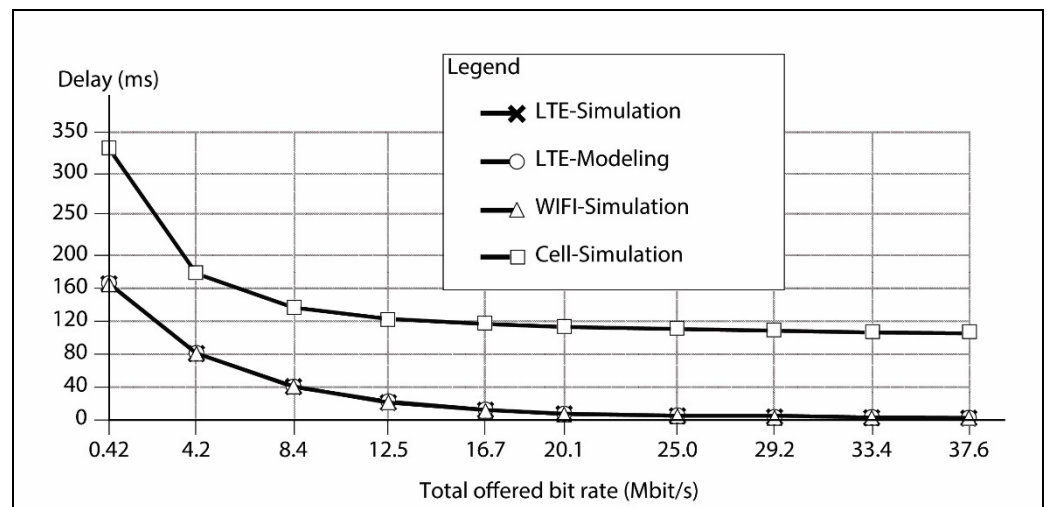


Figure 7. Delay with the coexistence.

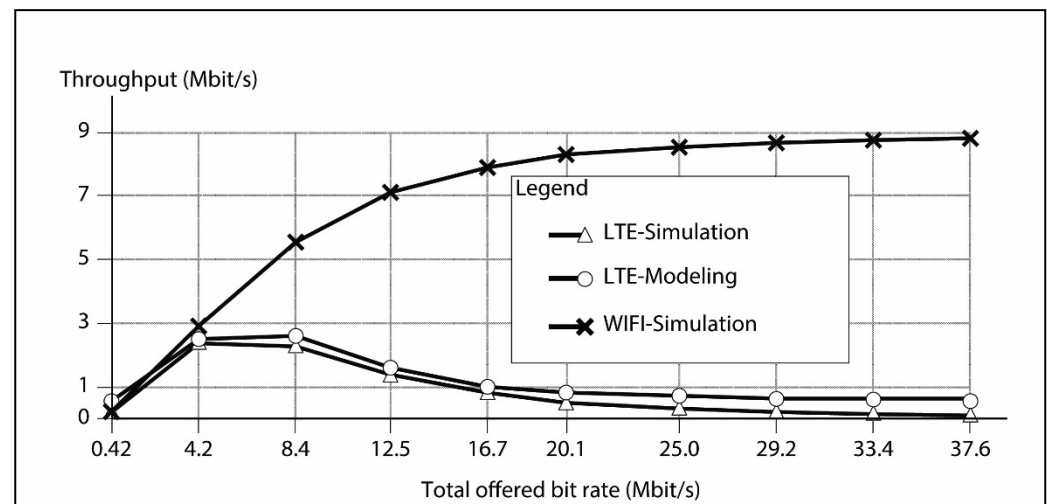


Figure 8. Throughput comparison.

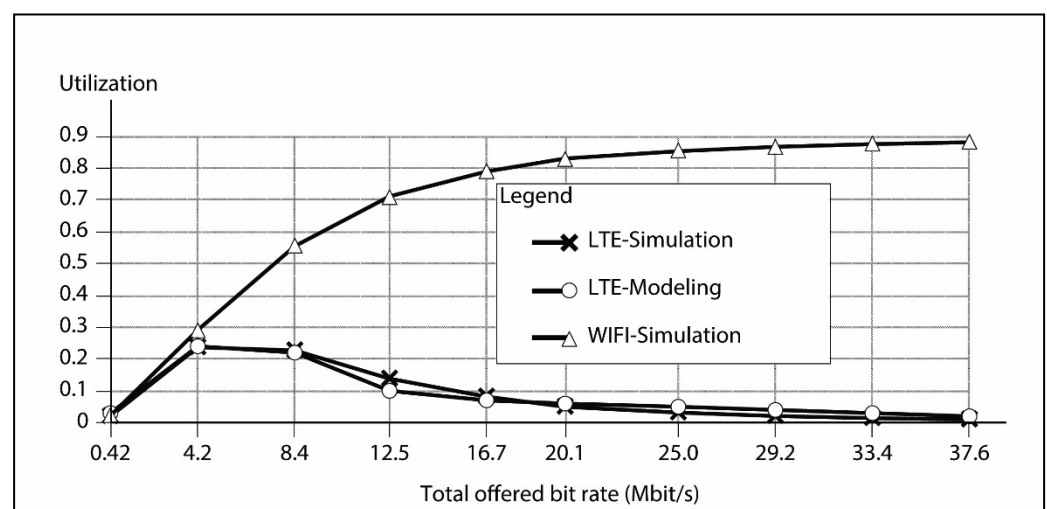


Figure 9. Utilization comparison.

The reason for this status is that STR needs a greater bandwidth than WB and, in the analysis, it was given a higher priority over WB. However, this necessary bandwidth for real-time streaming is only achieved at lower rates (i.e., less than 25 Mbit/s). On the other hand, when the load increases, this means that more people are downloading content from the Internet, and therefore the performance of the WB is maximized.

The AABR is presented in Figure 5 for the outer zone (zone 2). In this figure, very interesting results can be noticed. Below the offered bit rate of 16.7 Mbit/s, the AABR results are accomplished for all services; however, the VOLTE with the highest priority still has better results among the other services. Because most of the requests are served by the inner zone, above a 16.7 Mbit/s offered bit rate, all service performances reach a stable state. As the traffic increases, the performance reaches zero Mbit/s. In Figure 6, not only is the performance of LTE and Wi-Fi with coexistence shown, but the overall cell performance is also demonstrated to explain the effect of coexistence on cell performance as well.

LTE performance is degraded compared to Wi-Fi performance at different offered bit rates. Nevertheless, the main idea of the proposed integration and interoperability of both technologies is to provide better performance for the whole cell and the whole network, by distributing the load between both technologies so that the capacity of the network is maximized. Because of this achievement, it can be noticed from Figure 6 for the blocking probability results that the performance of the whole cell is maximized at different offered bit rates. Therefore, the main objective of the proposed model is achieved.

In Figure 7, the packet delay budget is given in milliseconds (ms). Agreeing with Table 3, one can notice that analogous delay budgets are attained for LTE and Wi-Fi, and, at higher total offered bit rates, it reaches the value of zero ms. Moreover, in the same figure, while both technologies coexist, the cell overall delay budget is also attained. For example, at the lower offered bit rate, the delay budget in the whole cell is around 340 ms; it reaches around 120 ms at the higher offered bit rate. On the other hand, an excellent performance or the delay budget is attained when both technologies coexist. It reaches around 160 ms for a low value of the offered bit rate and 0 ms at the maximum offered bit rate. It should be noticed here that, with this integration between both technologies, the best effort requests are served by the Wi-Fi zone, while requests that are more sensitive are left to be served by the LTE zone.

Thinking about real-life examples, assume you are walking in the mall while you are using your smartphone. Now, your smartphone automatically switches to the strongest signal, which is most probably the signal of Wi-Fi. However, when you need to access some sensitive information, then your smartphone switches to the signal of mobile data, which is LTE or 4G. This is why the throughput results of the Wi-Fi zone outperform the LTE zone at diverse offered bit rates, as shown in Figure 8. A similar manner can be observed for the utilization results shown in Figure 9. Since only high quality and sensitive data requests are served by the LTE zone, the Wi-Fi zone, which is responsible for most of the requests, outperforms LTE performance concerning utilization measures.

The comparative results with and without coexistence are demonstrated as the second group of results (Figures 10–12). These results are to compare the performance of both technologies with and without coexistence. Additionally, the figures show that LTE performance degrades while coexisting with Wi-Fi. Looking at Figure 10, one can notice that the LTE average bit rate is improved while functioning on its own. When coexisting with Wi-Fi, the performance dramatically degrades. On the other hand, some other figures prove the opposite. Figure 11 demonstrates the blocking probability, where better results are attained for LTE while coexisting with Wi-Fi. Moreover, wonderful results are shown in Figure 12, where a better delay budget can be achieved for LTE while coexisting with Wi-Fi. This status can be explained as follows: through coexistence, the traffic is divided between LTE and Wi-Fi; however, LTE still needs to serve some high-quality and sensitive requests while functioning on its own.

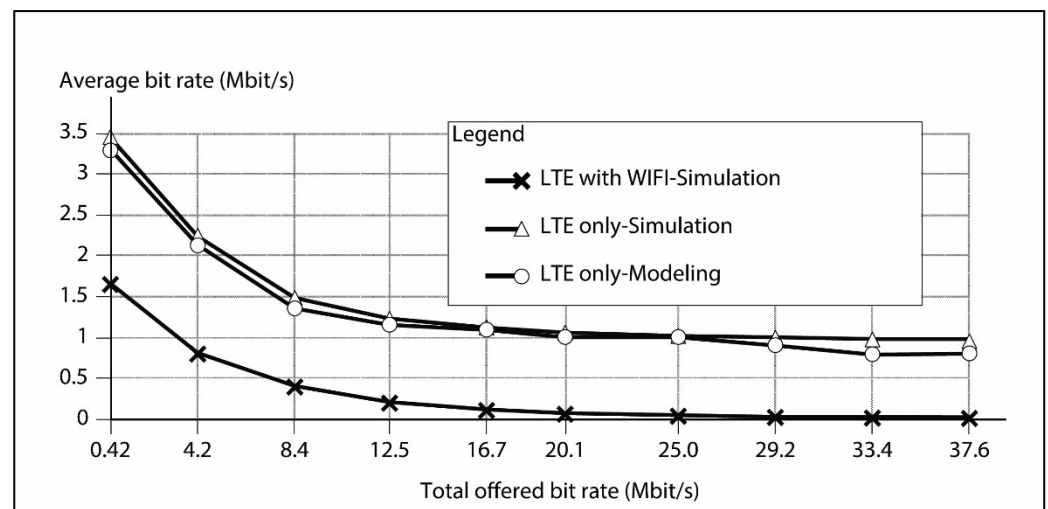


Figure 10. Average bit-rate comparison.

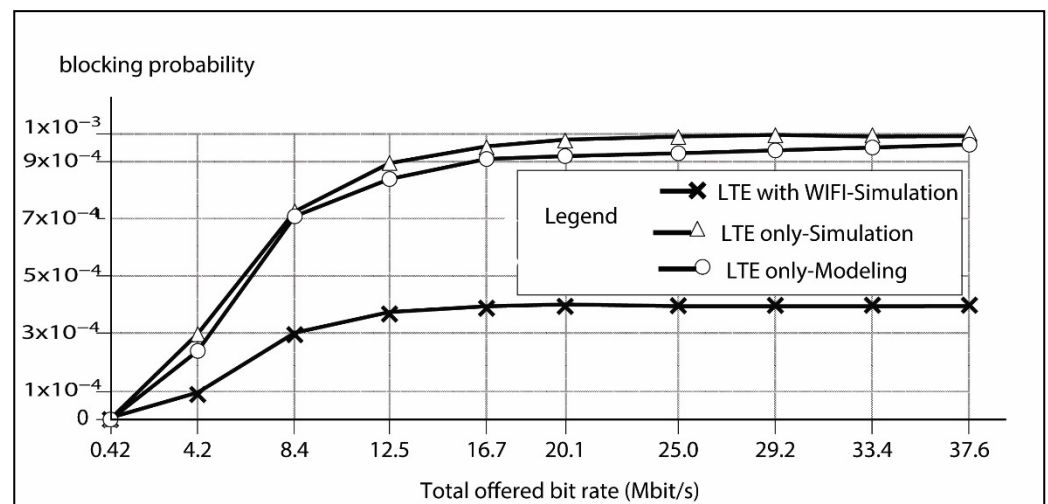


Figure 11. Blocking probability comparison.

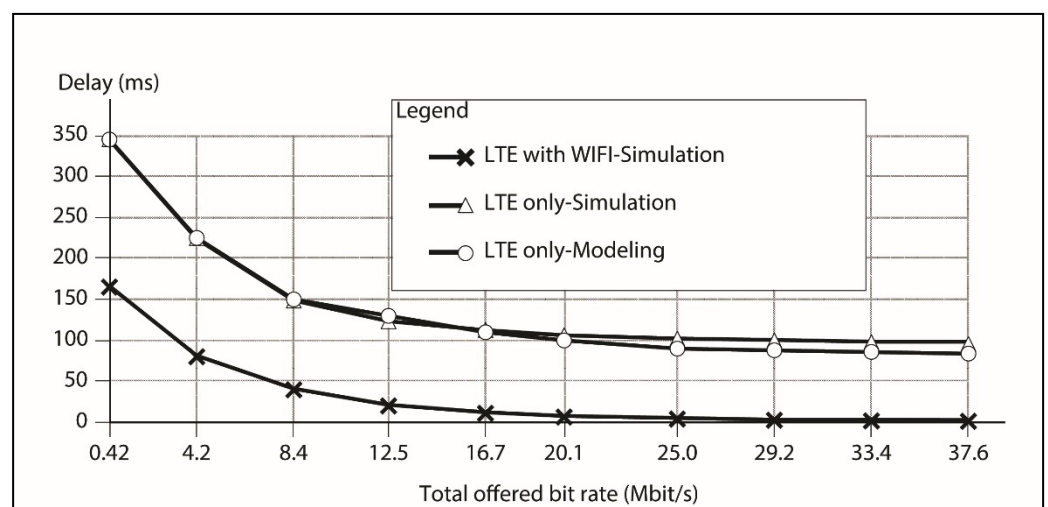


Figure 12. Delay comparison.

5. Conclusions and Future Work

Performance modeling and the analysis of integration/coexistence between LTE and Wi-Fi technologies in the downlink is proposed in this research. Via MOSEL-2 simulation, the numerical solution of the model is developed, and the model is solved mathematically to validate the numerical results obtained by MOSEL-2. The provided analysis and results confirm that, unlike other recommended models, the proposed coexistence model improves the overall cell performance by balancing the load to maximize cell capacity; however, it sometimes degrades LTE performance. Therefore, the main objective of this research is achieved by providing new service deployment strategies between LTE and Wi-Fi to achieve the maximum capacity on the network, while maintaining better QoS for the end-user. As per the team effort and experience in developing and solving the suggested model, numerically by the simulation and analytically by the mathematical solution, this new methodology can be used as a new tool that has an important commercial value for mobile operators. Therefore, the proper utilization of the above methodology and associated tools can help in proposing new deployment and integration scenarios to accomplish better network performance by maximizing the capacity of the network as well as achieving a better QoS for the end-user. The limitation of this approach is the possibility of including the mobility model and investigating the solution of the model in different propagation environments to be more realistic. Moreover, the possibility of comparing the results to similar scenarios as a future work can be beneficial. Furthermore, considering a multi-cell scenario, taking into consideration the handovers between different cells, is an excellent suggestion for future work. Finally, the integration between 5G and Wi-Fi technologies is another possible extension of the current work.

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